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THE NATURE *and* PROPERTIES OF SOILS

A COLLEGE TEXT OF EDAPHOLOGY

By

T. LYTTLETON LYON
Late Professor of Soil Technology Emeritus, Cornell University

HARRY O. BUCKMAN
Professor of Soil Technology Emeritus, Cornell University

AND

NYLE C. BRADY
Professor of Soil Science Cornell University

FIFTH EDITION

Revised by
HARRY O. BUCKMAN
and
NYLE C. BRADY

New York
THE MACMILLAN COMPANY

THE MACMILLAN COMPANY
NEW YORK • CHICAGO
DALLAS • ATLANTA • SAN FRANCISCO
LONDON • MANILA
BRETT-MACMILLAN LTD.
TORONTO

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Printed in the United States of America

Fifth Printing, 1956

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PREFACE

A COMPARISON of the status of Soil Science today with that of a decade ago will reveal advances in practically every phase. In some cases the changes, especially in viewpoint, have been almost revolutionary. The progress of the research on silicate clays is a case in point. The aim of the authors in writing the fifth edition has been to digest and evaluate this flood of new information and to incorporate it in a form even simpler than that of the preceding edition.

To attain this objective all but five of the original nineteen chapters either have been drastically revised or almost wholly rewritten. For example, the four chapters on soil water have been reduced to three and recast at a simpler level in order to better meet practical needs. In conformity with this new plan, much of the technical material relating to soil moisture has been set in smaller type and can be bypassed without materially weakening practical concepts. The same scheme has been employed in dealing with soil colloids, soil structure, and with fertilizer ingredients.

As a further aid to clarity as well as to interest, the number of illustrations has been more than doubled, half tones have been introduced, and the style of writing simplified. The use of numerous subheads should increase the readability of the text and at the same time better maintain the logical sequence of the presentation.

Moreover, the chemistry and physics employed lie well within the scope of that commonly taught to college freshmen. As a college text, therefore, this new edition is intended primarily for students of sophomore and junior status. There are, however, many practical features that we hope will attract other readers who are interested in soils and crops.

References are cited for two purposes, to establish authority for crucial statements and viewpoints and to assist the student who may wish to read more deeply into certain phases of Soil Science. Further than this, citations from an exceedingly voluminous literature are not attempted.

The authors have received aid and encouragement from so many sources that full recognition thereof is hardly feasible. However, when this help involved diagrams and half tones, acknowledgment is made in

the legends. Moreover, individual thanks are due to Marlin G. Cline, Professor of Soil Science, Cornell University, for his suggestions regarding soil classification and to Juan E. Reyna, Professor of Agricultural Engineering, Emeritus, Cornell University, for his constructive execution of our diagrams. For all this help the authors are exceedingly grateful.

H. O. Buckman
N. C. Brady

Cornell University
Ithaca, New York
April, 1952

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CHAPTER 1

The Soil in Perspective

THE SOILS that mantle our Earth are natural geologic bodies that have developed under a wide diversity of climate and of parent material. Hence, soils of many kinds have come into being. Furthermore, each individual soil presents a multitude of intricate and constantly varying processes. As a result, soils in the field are so complicated individually as to render their study extremely difficult. In fact, certain phases of their dynamic cycles have so far almost baffled scientific investigation.

Consequently, "soil science" as an organized body of facts has developed slowly. It is yet so incomplete that it often fails to deal satisfactorily with some of our most pressing practical problems. Only in recent years has it attained an entity of its own. It is now something more than a selective application of chemistry, physics, geology, and biology to this life-bearing Earth-veneer we call the soil.

Before considering in detail the many and varied phases of soil science, we shall subject this natural body to a broad over-all examination. This should prevent the misinterpretation of data and forestall serious misconceptions in respect to things of practical importance. Two paths of approach, or better two attitudes of mind, respecting the soil immediately present themselves—that of the *pedologist* in the one case and that of the *edaphologist* in the other.

1:1. THE APPROACH—EDAPHOLOGICAL RATHER THAN PEDOLOGICAL

Certain phases such as the origin of the soil and its classification and description are embraced in what is designated as *pedology*.[1] Pedology con-

[1] Pedology from *pedon* meaning soil or earth.

siders the soil purely as a natural body and lays minor emphasis on its immediate practical utilization. It is soil science in its more restricted form, yet in its systematic approach it freely employs all of the underlying sciences in the study of soil nature and genesis. Hence, pedology is more than mere scientific classification.

While pedology has yielded much valuable information, soil investigation to satisfy the layman must be pushed into wider and more practical fields. Since all animal and human foods come directly or indirectly from the soil, plant-production knowledge and skills are ever in demand. Hence, soil study, in the final analysis, must yield information of an agricultural and economic value. *Edaphology*,[2] an examination of the soil from the standpoint of higher plants, covers this broader but no less scientific aspect of soil inquiry. The ultimate, if not the immediate objective, of the edaphologist is crop production.

It is into this wider field that the reader is invited. Here the origin, the properties, and the classifications of soils—in short all that pedology has to offer—are viewed in an edaphological light. Here are studied the many interrelations of soils and plants, the principles of fertility maintenance, and the application of these principles to everyday practices. Even hypothesis and speculation will be pressed into service as tentative explanations are sought for phenomena arising from the interrelations of soil and plant and climate.

Before beginning a detailed consideration of this edaphological approach, it is perhaps advisable to explain very briefly how soils are formed and describe some of their field characteristics.

1:2. SOIL GENESIS—A BIOCHEMICAL PHENOMENON

Land surfaces almost everywhere are covered with unconsolidated debris called the *regolith*. This mantle above the bedrock may be negligibly shallow or it may be hundreds of feet in thickness. Moreover, it is notably heterogeneous since its physical and chemical characteristics may vary not only from one location to another but at a given spot may vary considerably with depth. In addition, its geological origin is not always the same even within restricted areas. This regolith has attained its position either

[2] Edaphology from *edaphos* also meaning soil or ground. The term *edaphology* was suggested by Dr. Horace L. Jones, Professor of the Classics, Emeritus, Cornell University. Its meaning was formulated by the authors of this text.

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through transportation and deposition by water, wind, or ice, or by the weathering in place of the country rocks.

Since the upper part of this variable regolith[3] is in contact with the atmosphere, weathering here usually is comparatively rapid. Hydrolysis, hydration, oxidation, carbonation, and solution accompany the physical changes that are taking place. And when microorganisms and higher plants have gained a foothold, organic matter tends to accumulate on and in the surface layer. Naturally this component is subject to rapid decomposition. It is at this point that accelerated soil formation really begins and a differential layering appears that can be ascribed largely to the influence of living organisms. In fact, a true soil cannot be formed without the presence and decay of some organic matter.

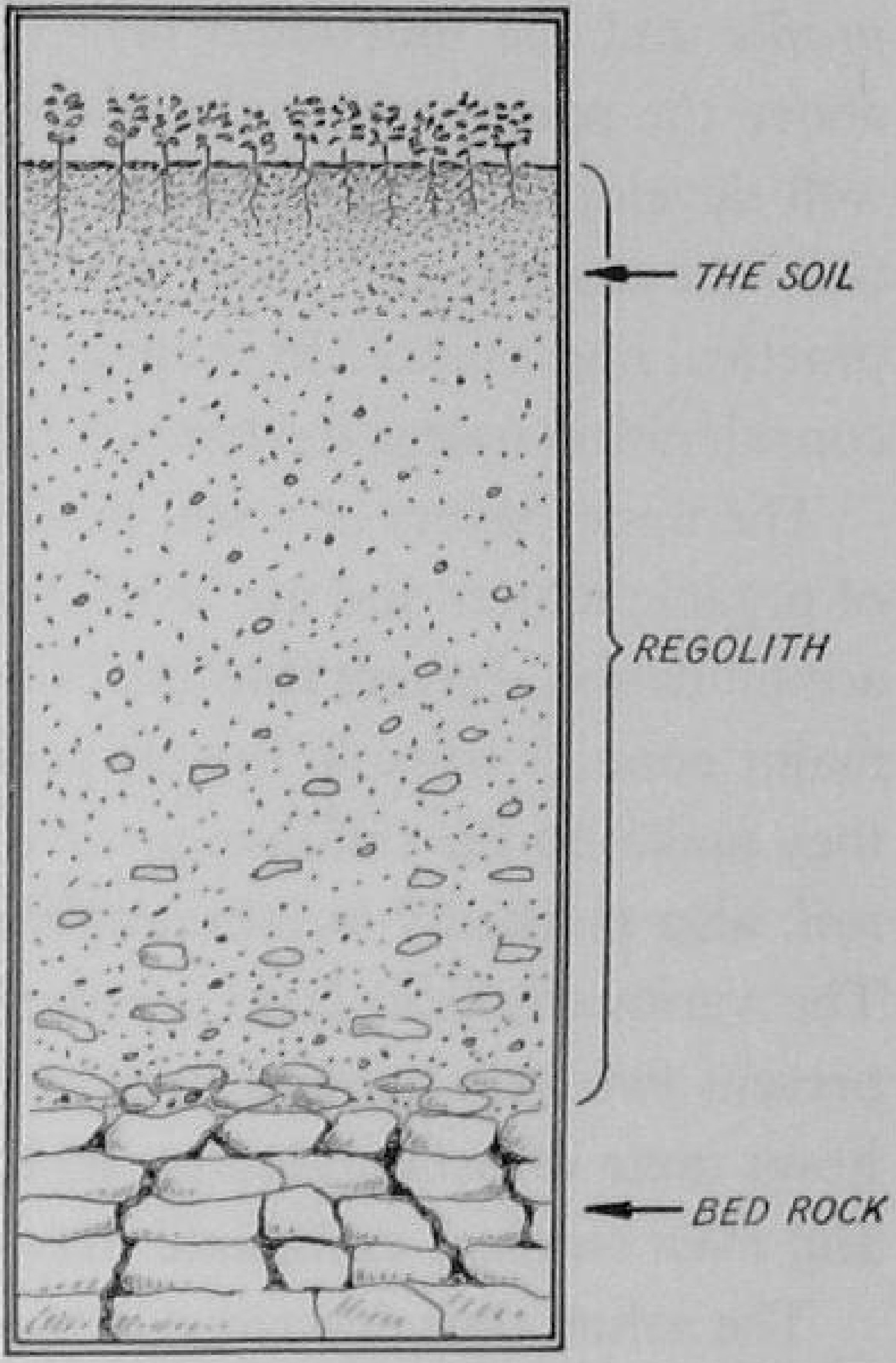

FIG. 1:1. *Diagram showing the relative positions of the regolith, its soil and the underlying country rock. Sometimes the regolith is so thin that it has been changed entirely to soil, which, in such a case, rests directly on bed rock.*

Mere physical and chemical weathering of rocks, therefore, should not be confused with soil formation as most soil processes are directly or indirectly biological in nature. The soil is thus a natural body, distinct from, yet transitional to, the parent material. It is the upper and biochemically weathered portion of the regolith. (See Fig. 1:1.) This concept of soil formation may be schematically represented as follows:

Upper layer ⟶ "Parent Material" ⟶ "Soil"

"Bedrock" ⟶ to ⟶ "Regolith"

Physical and Chemical Weathering (Little or no organic matter is present)

Bio-chemical Weathering (Addition and decay of organic matter are essential features)

[3] The regolith includes all of the unconsolidated material above the bedrock. Hence, the soil is a part of the regolith. See Fig. 1:1.

1:3. THE SOIL PROFILE[4]

If a section downward through a representative soil is examined, a layering, often well defined, will usually be found. Such a section is called a *profile* and the individual layers are regarded as *horizons*. The horizons above the parent material are collectively referred to as the *solum*.[5] Every well developed undisturbed soil has its own distinctive profile characteristics. These are made use of in soil classification and survey and are of great practical importance. In judging a soil its whole profile should be taken into consideration unless its depth is far beyond that of normal root penetration.

The upper layers of a soil profile generally contain considerable amounts of organic matter and are usually darkened appreciably because of such an accumulation. Layers thus characterized are conveniently referred to as the major zone of organic matter accumulation. When plowed and cultivated, they make up the familiar *surface soil* or furrow-slice. The underlying *subsoil,* also markedly weathered, contains comparatively less organic matter. The various subsoil layers, especially in mature humid region soils, often present two very general belts, (1) an upper zone of transition and (2) a lower zone of accumulation. In the latter, iron and aluminum oxides, clay and even calcium carbonate may gradually concentrate. (See Fig. 1:2.)

The solum thus described extends an indefinite but moderate depth below the surface. A depth of 3 or 4 feet is representative for temperate-region soils. Here the noticeably modified lower subsoil gradually merges with the less weathered portion of the regolith. This part of the regolith is called the *parent material* to distinguish it from the soil just above. It is usually weathered, sometimes markedly so, and its upper portion is, geologically, on the point of becoming a part of the lower subsoil and hence of the soil solum.[6]

It is not to be inferred that the various layers comprising a soil profile, and they sometimes number five or six, are always distinct and well defined. In fact, the transition from one to the other often is so gradual that the establishment of boundaries is rather difficult. This is likely to be true in respect to the subsoil horizons. Nevertheless, for any particular soil[7] the

[4] A more technical and critical consideration of the soil profile will be offered later. See page 325.

[5] *Solum*—a latin law term meaning soil; land; or parcel of land.

[6] Remember that the soil *solum* and the *parent material* are both a part of the regolith.

[7] A *soil,* as distinguished from *the soil,* is merely a well-defined subdivision based on profile characteristics and is more or less identical throughout its lateral range.

various horizons are characteristic and greatly influence the growth of higher plants. This is especially true of the surface and the upper subsoil.

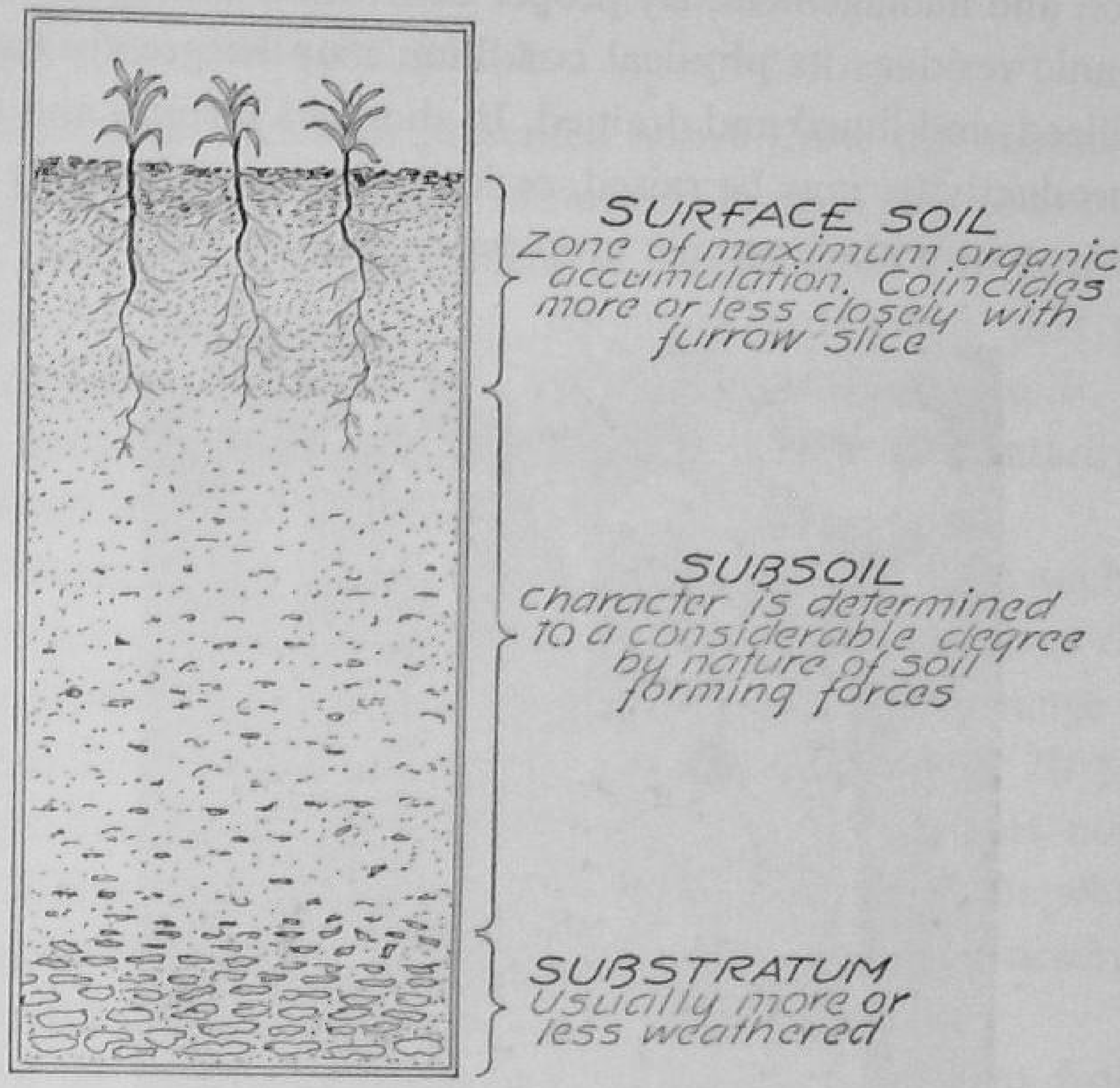

FIG. 1:2. *A representative soil profile. The surface horizons are relatively high in organic matter and become the furrow slice when the land is plowed. The subsoil, while markedly weathered, usually contains but little organic matter. At variable depths it merges more or less gradually into the substratum (parent material). All of the layers above the substratum are spoken of collectively as the* solum.

1:4. SUBSOIL VS. SURFACE SOIL

The productivity of a soil is determined in no small degree by the nature, both physical and chemical, of its subsoil. The practical importance of this fact is seen when we consider that the subsoil normally is subject to little field alteration except by drainage. Even when roots do not penetrate deeply into the subsoil, its permeability and its chemical nature still may favorably or unfavorably influence the surface soil as a medium for plant growth. Soil productivity depends to no small extent on subsoil characteristics. (See Fig. 1:3.)

The situation in respect to the surface soil is in distinct contrast. In the *first* place, it is the major zone of root development, it carries much of the nutrients available to plants, and it supplies a large share of the water used

by crops. *Secondly*, instead of being stable and fairly static, it is dynamic and subject to comparatively easy change. As a furrow slice it is subject to manipulation and management. By proper cultivation and by the incorporation of organic residues its physical condition may be greatly modified. It can be fertilized, and limed and drained. In short, its fertility and to a lesser degree its productivity, may be raised, or lowered or satisfactorily stabilized at levels consistent with economic crop production.

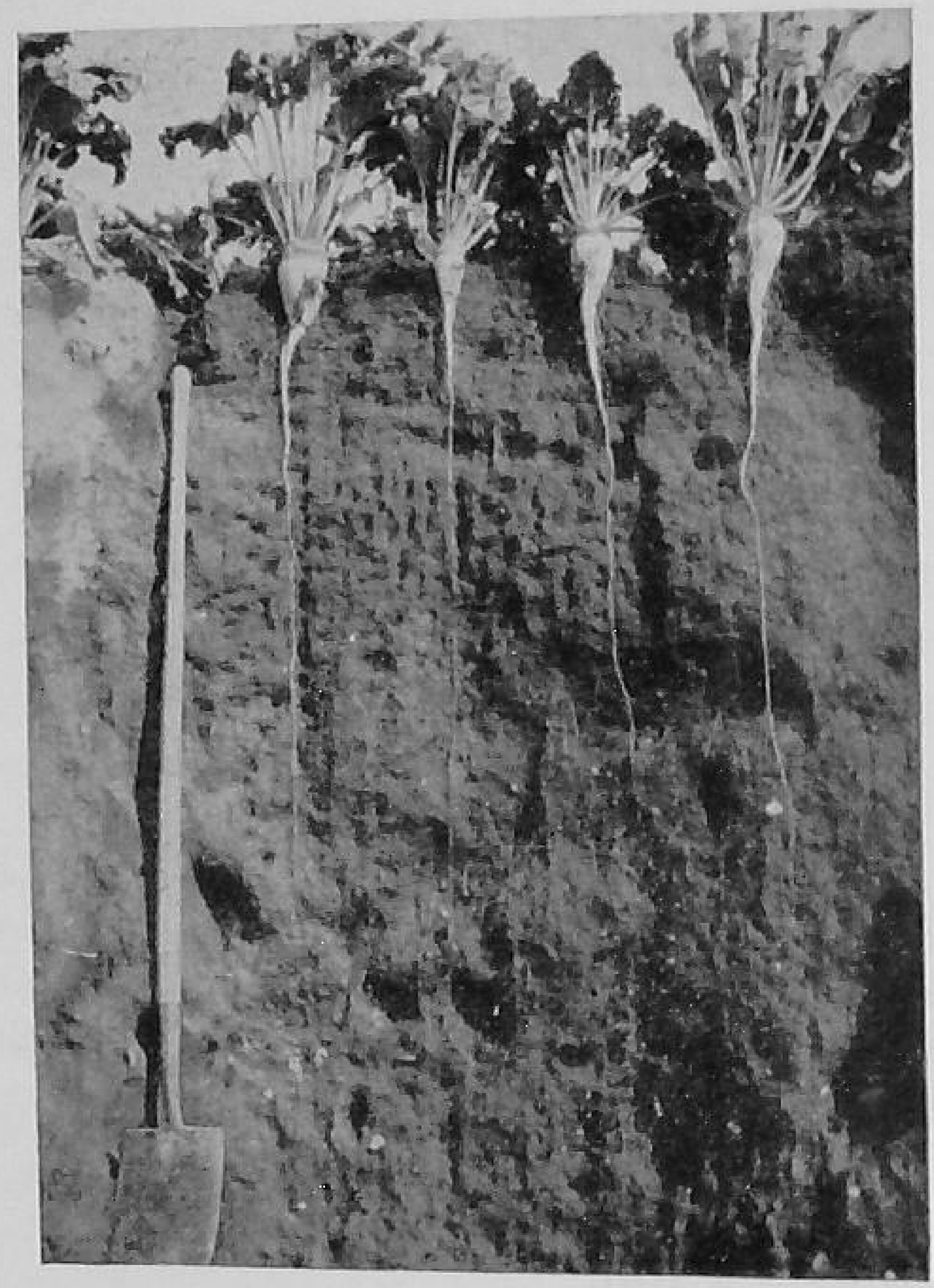

FIG. 1:3. *Deep rooting plants such as sugar beets must have a porous subsoil for most satisfactory growth. In the case pictured the crop undoubtedly is obtaining large amounts of mineral nutrients as well as water from the subsoil or even from the substratum. A fairly permeable subsoil is especially desirable where irrigation is practiced. (The Great Western Sugar Company Photo.)*

This explains why much of the soil investigation and research, especially that of an edaphological nature, has been expended upon the surface layer. It also explains why most of the discussion and explanation that follow, the data quoted, and the conclusions drawn concern themselves with surface soils. Plowing, cultivation, liming and fertilization are essentially furrow-slice considerations. In fact, the term *soil* unmodified will from

here on be taken as reference to the surface layer, the so-called topsoil, or in practical terms, the furrow-slice.

1:5. MINERAL VS. ORGANIC SOILS

The profile generalizations presented above show the organic matter to be largely in the surface horizon. Moreover, even in this zone the amounts are always comparatively low, ranging in general from 1 to 5 or 6 per cent. Because of the predominance of inorganic constituents that necessarily results, such soils are conveniently referred to as *mineral soils.* Most soils are of this nature and are so common that a person involuntarily thinks of this type when the term soil is mentioned.

But in swamps, bogs, and marshes, conditions are often such as to encourage the accumulation of much organic matter. This gives rise to peat deposits and peat soils in which the organic content may range as high as 95 per cent. Perhaps 80 per cent of organic matter and 20 per cent of minerals are reliable representative figures for the deposits now used as field soils. Moreover, a high organic content characterizes the whole profile, quite in contrast with the mineral soil sections already described. (See Fig. 13:1.) As such they are referred to as *organic soils.*

As might be expected, peat soils are markedly different from mineral soils in many important respects and their practical handling presents problems that are both distinctive and unique. In spite of their smaller area these soils are very important for certain crops, especially those, such as vegetables, which respond to intensive culture.

Not only are mineral soils of wider area and are better known than are organic soils, but also they are in general more important agriculturally. Moreover, most of our pedological and edaphological study and theory relate to such soils. Consequently, mineral soils deservedly receive the major attention in this text, the origin, character, and agricultural use of peat soils being considered as a unit in Chapter 13. Until then the discussion will concern itself almost exclusively with mineral soils.

1:6. AN EDAPHOLOGICAL CHARACTERIZATION OF MINERAL SOILS

Mineral soils have already been designated as the "upper and biologically weathered portion of the regolith." This is a formal and wholly inadequate statement in itself, but when expanded by profile and horizon study, it presents a pedological concept of soil origin and characterization.

If, however, the production of higher plants is to be a part of the picture, a broader and more inclusive statement must be offered. In the light of the ideas already presented respecting the general function of the soil, the following edaphological definition is suggested:

"The soil may be defined as a natural body, synthesized in profile form from a variable mixture of broken and weathered minerals and decaying organic matter, which covers the earth in a thin layer and which supplies, when containing the proper amounts of air and water, mechanical support and, in part, sustenance for plants."

1:7. FOUR MAJOR COMPONENTS OF SOILS

The definition just cited leads logically to an inquiry as to soil composition. This will be dealt with here in a very general way. Mineral soils, especially when in an optimum condition for the growth of higher plants, consist in a broad way of four components: namely, *mineral materials, organic matter, water,* and *air*. These in the main are in a rather fine state of subdivision and are intimately mixed. In fact, the contact is often so close as to render satisfactory separation rather difficult.

Mineral material, which comprises the bulk of soil solids, has its original genesis in the regolith or more specifically in the parent material. Some of the soil minerals such as quartz have persisted more or less unchanged, while others have developed as the regolith weathered, either before or during soil formation. Clay is a good example of this latter group. Naturally, various sizes of particles occur, ranging from those that are comparatively coarse, such as gravel and sand, to those, such as silt and clay, that are in a very fine state of division.

The soil organic matter represents the accumulation of plant and animal residues and is generally in an active state of decay. Such material, because it readily succumbs to the attack of microorganisms, is a rather transitory soil constituent and requires constant renewal. A sample of a dry upland mineral top soil, as already suggested, usually contains from 2 to 6 per cent of total organic matter compared with 94 to 98 per cent of inorganic substances.

An examination of any soil will reveal the presence of pore spaces of varying sizes. These occur not only between the large, solid particles but also between and within the clumps and aggregates which the finer particles tend to form. These clumps usually are better developed in the surface layers and when the soil is in a suitable physical condition for plant

growth. The pore spaces, variable as to continuity and size, are occupied by water and air, the proportions depending on the character and management of the soil.

Water, the third component of the soil, is held within these pore spaces with varying tenacity due to certain surface forces. Some passes readily from place to place, while some moves hardly at all. In all cases, surface contacts are paramount. Due to the action of the water itself and that of carbon dioxide and other substances present in soil water, some solution occurs continuously even though the soil solids generally are not easily dissolved. Soil water for this reason carries many soluble salts, the concentration of which varies greatly from time to time and from soil to soil.

The principal gases of the soil air, the fourth component, are nitrogen, oxygen, and carbon dioxide. The first is very inert and enters into chemical reaction only when taken up by certain bacteria, called *nitrogen fixers.* (See page 144.) By them it is built into complex organic compounds. Oxygen is, of course, essential for all life forms, whether the roots of higher plants or the tiniest bacteria. The carbon dioxide, by reacting with the soil water, produces carbonic acid, one of the most important acids found in soils. Carbon dioxide also serves as a source of carbon for special types of microorganisms. This mixture of nitrogen, oxygen, and carbon dioxide not only varies inversely with the amount of water present in the soil but also is extremely variable as to the ratio of the gases present.

1:8. THE VOLUME COMPOSITION OF MINERAL SOILS

Once the identity of the four soil constituents is established, the question as to their relative proportions is sure to be raised. As to this, the surface soil will be considered first, leaving the subsoil for later examination. For simplicity of statement the representative surface soil when dry may be considered to contain by weight approximately 4 per cent of organic matter and 96 per cent of mineral material. But this leaves entirely out of consideration the air and water, a serious omission since these constituents have so much to do with the activity of a normal soil. If a quantitative concept, truly significant, is to be realized, the volume basis of representation must be used.

A silt loam surface soil will be considered as more or less representative. When such a soil is in optimum condition for plant growth, it contains by volume approximately 50 per cent of solids and 50 per cent of pore space. The pore space will be somewhat less for sandy soils and somewhat greater

for soils of a more clayey nature—especially if they are granular. The 50 per cent of solid space is made up of about 45 per cent of mineral and 5 per cent of organic substances by volume. At optimum moisture for plant growth, the 50 per cent of pore space possessed by this representative silt loam is divided roughly in half—25 per cent of water space and 25 per cent of air. The proportion of air and water is, of course, subject to great fluctuations under natural conditions, depending on the weather and other factors. (See Fig. 1:4.)

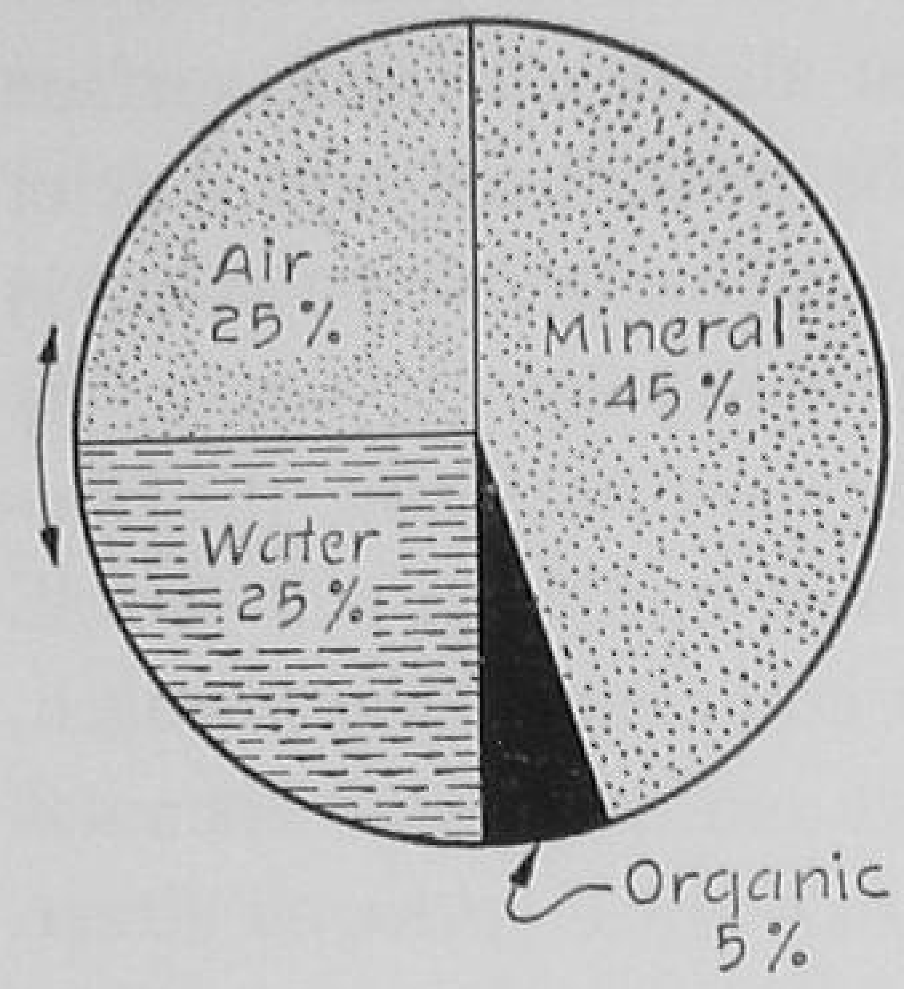

FIG. 1:4. *Volume composition of a silt loam surface soil when in good condition for plant growth. The air and water in a soil are extremely variable, and their proportion determines in large degree its suitability for plant growth.*

In presenting such an arbitrary volume representation of a surface mineral soil, it must be emphasized that the four main components of the normal soil exist for the most part in an intimately mixed condition. Also, very complex reactions occur with surprising ease and rapidity within and between the groups. Contact, or *interface,* reactions are especially important. Unless such interactions take place, this complex heterogeneous mass cannot long remain in a condition, either physically or chemically, that will suitably support plant life.

No attempt will be made to establish even a tentative volume composition for the subsoil. Suffice to say in most cases, especially with soils inclined to be clayey, the pore space is much less than that of the surface soil and the individual pores are smaller. This is to be expected as there usually is insufficient organic matter to promote porosity and thereby offset natural compaction.

The downward movement of clay also tends to fill up the subsoil pore spaces, sometimes causing a decidedly impervious condition called a *clay pan.* Actual cementing may even occur, especially with iron oxide, and a true *hardpan* is thus developed. Silica under certain conditions may function in the same way. All in all, the subsoil is likely to be more compact and less pervious to air and water than the furrow-slice. This means, on the volume basis, a higher percentage of minerals and a considerably lower content of organic matter and air. Thus the aeration and drainage of all subsoils become of great practical concern and should not be overlooked in judging the agricultural value of land.

1:9. THE MINERAL CONSTITUENTS OF SOILS

It is, of course, obvious that the original source of the inorganic constituents of a mineral soil has been the rocks common at the earth's surface. The best known country rocks,[8] such as limestone, granite, sandstone, and shale, present the greatest outcrop surface. Of necessity, they have contributed most to the regolith, to the parent material, and hence to the soil itself.

Two types of minerals are present in the soil: those that have persisted more or less unchanged from the original rock, and those that have been formed by the weathering of less resistant fragments as the regolith developed and soil formation progressed. The former are called *original* minerals and the latter, *secondary*. For example, the quartz grains of a soil almost always come directly from the original rock, as do such particles of feldspar, mica, hornblende, epidote, and garnet that happen to persist. On the other hand, hematite, limonite, gypsum, and such clay minerals as kaolinite, as well as other secondary silicates, seem to have originated mostly through the weathering of some of the original minerals.[9]

[8] Some of the more common country rocks are as follows:

Igneous	*Sedimentary*	*Metamorphic*
Granite	Limestone	Gneiss
Syenite	Dolomite	Schist
Diorite	Sandstone	Slate
Gabbro	Shale	Quartzite
Basalt	Conglomerate	Marble

[9] The more important soil minerals may be listed as follows:

Original Minerals [a]

1. Quartz	SiO_2
2. Microcline and orthoclase	$KAlSi_3O_8$
3. Plagioclase feldspars	Ca and Na aluminum silicates
4. Muscovite and biotite	K, Mg, Fe, and H aluminum silicates
5. Hornblende and augite	Ca, Mg, and Fe aluminum silicates
6. Calcite and dolomite	$CaCO_3$ and $CaMg(CO_3)_2$
7. Apatite	Apatite, $Ca_5(PO_4)_3{\cdot}(Cl, F)$

Secondary Minerals [b]

1. Various clay minerals	Complicated aluminum silicates
2. Hematite	Fe_2O_3
3. Limonite compounds	Typified by limonite $2Fe_2O_3{\cdot}3H_2O$
4. Secondary calcite	$CaCO_3$
5. Secondary gypsum	$CaSO_4{\cdot}2H_2O$
6. Secondary phosphates	Oxy-, hydroxy- and carbonate apatites
7. Secondary mica	Typified by sericite and illite

(*Cont'd on next page*)

The mineral particles of the soil may be classified according to size under four heads as follows:

1. Very coarse	Visible to the naked eye	Stone and gravel
2. Coarse	Visible to the naked eye	Sands of various sizes
3. Fine	Visible under ordinary microscope	Silt particles both coarse and fine
4. Very fine	Visible satisfactorily only under electron-microscope	Clay particles—highly colloidal [10]

The last three grades are the most desirable as components of arable soils and commonly predominate. They are referred to collectively as *fine earth.* While the rounded or quite irregular sand grains usually are quartz, other minerals may occur such as hornblende, augite, mica, garnet, epidote, and magnetite. (See Figs. 3:1 and 3:3.) Among the larger sand particles, fragments of sandstone, shales, granite, and other rocks are commonly found. Stone and gravel are seldom made up of single minerals, but are usually rough or rounded fragments of rocks.

The silt particles, as to source, are in large part original. They are in a sense microscopic sands. Their interior is generally more or less unweathered, while their outer and irregular surfaces are usually coated with clayey matter. When free of this coating, silt is only slightly plastic, cohesive, and adsorptive. Silt in most soils is made up largely of quartz with an admixture of other primary minerals.

The clay particles because of their fineness of division are in a highly colloidal condition. In mass they are viscous and gelatinous when moist, but hard and cohesive when dry. Clay minerals, therefore, endow the soil with outstanding physical properties that are well recognized in practice. Moreover, their attraction for ions in the soil, one of the notable characteristics of most colloidal matter,[11] has much to do with the retention of nutrients and their availability to plants.

Thus it is evident that the representative mineral soil is a mixture of

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[a] Other minerals of this group are garnet, zircon, magnetite, rutile, epidote, tourmaline, and olivine.

[b] Other minerals that may be of secondary origin are serpentine, chlorite, epidote, talc, etc. Some of these so-called secondary minerals may have become in the course of their geological cycle a part of the bedrock. They are, nevertheless, still secondary in a geologic sense and will be so considered pedologically. Thus, hematite is a weathering product whether its formation was coincident with the development of the regolith and its accompanying soil or was formed long before in some previous cycle of weathering.

[10] Various grades of clay particles are recognized such as coarse, fine, and very fine. The two finer groups, especially the ultra-clay, are referred to as colloidal.

[11] For a brief explanation of the colloidal state of matter see page 79.

particles differing markedly in size and shape, in chemical composition, in mineralogical nature, and in physical and chemical properties. The particular group or groups of particles that dominate an individual soil largely determine the characteristics of that soil and have much to do with its fertility and its productivity.[12]

1:10. THE SOIL ORGANIC MATTER

One of the essential differences between a productive surface soil and a mere mass of rock fragments, however fine, lies in the organic content of the former. But the amount of organic matter present is so small—only about 4 per cent in the case of the representative mineral soil—that it might be considered of minor significance, especially in comparison with the 96 per cent of mineral materials present. In answer to this, one need only to state that organic matter is necessary for soil formation. Moreover, practically all of the nitrogen and a large proportion of the phosphorus and the sulfur of the soil are held in organic combinations. Therefore, when the organic matter begins to fail, these essential elements must of necessity become critical.

Again the organic matter has much to do with the physical condition of soils, especially those of a clayey nature. It promotes the aggregation of the soil particles, increases the water-holding capacity, and makes the creation of a satisfactory seedbed more easy and rapid. In addition, the organic matter is the main source of energy for soil microorganisms. Without it, biochemical activity would come practically to a standstill.

For convenience, the soil organic matter may be considered to consist of two general groups: (1) original tissue and its partially decomposed equivalents, and (2) the humus. The original tissue includes the more or less undecomposed additions that are constantly being made. Normally these additions are mostly of plant origin—the roots and tops of higher plants, as well as the remains of fungi and bacteria—although some animal tissue is received from rodents, earthworms, protozoa, and the like.

If conditions are at all favorable, soil organisms, both plant and animal, vigorously attack the added organic matter using it as a source of energy and as a tissue-building material. The original additions and the resultant intermediate products are thus rapidly resolved to *humus*—the black or

[12] The term *fertility* refers to the inherent capacity of a soil to supply nutrients to plants in adequate amounts and in suitable proportions. *Productivity* relates to the ability of a soil to yield crops. Productivity is the broader term since fertility is only one of a number of factors that determine the magnitude of crop yields.

brown material so noticeable in the surface layers of most soils. In reality, humus is a synthesized residue of biochemical decomposition, both direct and indirect, and is very complex.[13] It is the more resistant portion of the soil organic matter. Mixed with it will be found fragments of plant tissues and the bodies of various soil organisms, both alive and dead.

As humus is synthesized many simple compounds of great importance appear. Carbon dioxide is evolved, often in large quantities, while at certain stages, nitrates, sulfates, and other rather soluble and available products are much in evidence. At the same time, energy from organic matter is liberated as heat or is used freely by soil organisms. In fact, most of the tangible energy of the soil is that of the organic matter.

In common with other types of matter in the colloidal state, the soil humus exhibits adsorption to a very unusual degree. In its capacity to attract and hold water, gases, and ions, humus, pound for pound, greatly exceeds the clayey colloids. Small amounts of humus augment tremendously the dynamic characteristics of a soil.

1:11. SOIL WATER—A DYNAMIC SOLUTION

As water circulates through the intimately mixed mass of decomposing mineral and organic matter of the soil, it of necessity becomes a solution bearing at least traces of every element present. However, the mistake is often made of considering this soil solution in its relationships to higher plants as a simple water culture such as is used in botanical laboratories. The latter presents a continuous liquid body which is not greatly influenced by undissolved solids. It is, therefore, rather homogeneous.

The soil solution, however, is in marked contrast. It is greatly dispersed and exists, in part at least, in minute subdivision. Moreover, the water itself, as well as the dissolved cations, suffers intense adsorption as it contacts the immense surface exposed by the colloidal solids. Thus, some of the water is held tightly and has little movement, while some is free to adjust readily from place to place. Also the concentration of ions because of their adsorption is greater in the immediate neighborhood of the colloidal surfaces. The soil solution may, therefore, be characterized as heterogeneous both in movement and in concentration.

Moreover, the soil solution is highly dynamic both as to amount and concentration. Rain, evaporation, and plant action obviously tend to vary its total amount. When such fluctuations are accompanied by varying rates

[13] For suggestions as to the synthesis of humus, see page 158.

of solution, losses of nutrients to higher plants and to drainage, radical changes in concentration and composition are sure to occur. Additions of fertilizers, lime, and farm manure intensify these dynamic tendencies.

In such a fluctuating medium, higher plants as well as microorganisms must adjust themselves to a great variety of conditions. This is often rather difficult. For example, higher plants and other soil organisms must adapt themselves to frequent changes in the quantity of soil moisture present. Variations in the concentration and proportions of the various ions present in the soil solution must also be met. The soil solution is thus unique and by no means comparable to an ordinary water culture.

1:12. THE SOIL AIR—ALSO A CHANGEABLE CONSTITUENT

One of the common misconceptions is to consider the soil air as merely a continuation of the ordinary atmosphere into the soil. In the first place, the soil air is not a continuous gaseous body as is the atmospheric air but is highly dispersed and adsorbed by the soil colloids. Moreover, some may be dissolved in the soil water. Again its humidity, when soil moisture is at optimum for higher plants, approaches 100 per cent (see Fig. 7:11), a condition especially favorable for the development of fungi, bacteria, and other soil organisms.

Due to the activity of these organisms the carbon of the soil organic matter is readily oxidized and large amounts of carbon dioxide are more or less continuously evolved. The process, being essentially one of oxidation, at the same time ties up oxygen in roughly equivalent amounts. Hence, the soil air, while differing but little from that of the atmosphere above in respect to the inert nitrogen, is markedly higher in carbon dioxide and often considerably lower in oxygen. In general the air of the pore spaces unfilled with water contains several hundred times more carbon dioxide than does the air above the soil for which .03 per cent by volume is a representative figure. The oxygen on the other hand may sink from 20 per cent, the approximate figure for atmospheric air, to as low as 10 or 12 per cent, a level which does not provide adequate aeration for the roots of most plants.

A carbon dioxide feature that deserves especial mention is this. When this gas contacts water, carbonic acid (H_2CO_3) is formed. Since this acid ionizes slightly, H-ions instantly appear and the acidity of the soil solution tends to increase. In most cases the evolution of carbon dioxide is copious enough to maintain a definite and more or less constant H-ion concen-

tration in the soil solution. Since H-ions promote reactions of tremendous importance both physically and biochemically, this interrelation between the soil air and the soil solution will be referred to again and again. It is an equilibrium reaction of vital moment. (See page 274.)

As might be expected, the soil air is markedly heterogeneous as to position, as to movement, and as to composition. Some is in close contact with the soil solids. Such air is likely to be very high in carbon dioxide and has slow, if any, movement. Some, on the other hand, occupies the larger spaces, is free to move from place to place, and usually contains adequate quantities of oxygen and a minimum of carbon dioxide.

Besides these types of heterogeneity, the atmosphere of the soil is dynamic, changing constantly in amount and composition. A fluctuation in the quantity of soil water automatically varies the amount of air present, while any condition that increases or decreases microbial activity and carbon dioxide production must certainly modify the proportion of the various gases present.

The soil air [14] because of its varying amounts of carbon dioxide and oxygen, presents to the roots of higher plants and to microorganisms an atmosphere suited to almost any type of biochemical activity. Aerobic and anaerobic organisms flourish side by side while reduction and oxidation may occur simultaneously in the same soil horizon. The dynamic nature of such an atmosphere is such as to force rapid adjustments upon any plant or animal that attempts to function within it. This is a phase that must be reckoned with in biological studies of field soils.

1:13. THE SOIL—A TREMENDOUS BIOLOGICAL LABORATORY

The representative mineral soil, bearing as it does so much available energy in organic form, harbors a varied population of living organisms. Nature is most lavish in this respect. Indeed, the *life* of the soil plays such a prominent and indispensable role in the changes constantly occurring, that no discussion of the soil is complete without its consideration.

Representatives of both animals and plants are abundant in soils. Some of the organisms are large while others are very small. The whole range from the larger rodents, worms, and insects to the tiniest bacteria commonly occurs in normal soils. Moreover, most organisms vary so much both in numbers and amounts as to make precise statements impossible.

[14] For a more detailed consideration of soil air see Chapter 10, page 274.

For example, the number of bacteria alone in a gram of soil may range from 100,000 to several billion, depending on conditions.

The total weight of living matter, including plant roots, in an acre-furrow-slice of a representative mineral soil may be placed at 5,000 pounds at least, while 10,000 or even 20,000 pounds may be more nearly correct for many soils. In any case the quantity of living organic matter is sufficient to influence profoundly the physical and chemical trend of soil changes. Indeed it can even be said that "practically all natural soil reactions are directly or indirectly biochemical in nature."

Of the larger organisms, the influence of the earthworms is perhaps in general the most important. (See Fig. 5:2.) Besides translocating and mixing the soil, these animals pass large quantities through their bodies. Such earth is thus subjected to certain digestive processes, which must have considerable influence on its physical and chemical nature. The organic matter, which furnishes the earthworms with energy and with most of their tissue-building materials, undoubtedly is changed in greater degree by the processes of digestion than are the mineral substances present.

Other and perhaps better examples of the biological influences brought to bear on the soil, especially upon its organic constituents, may be obtained by turning to the fungi and bacteria. (See Fig. 5:5.) These forms, more perhaps than any others, determine the rate and character of organic synthesis and simplification. They govern by their enzymic activity the nature of the humus and control the volume of carbon dioxide produced. The appearance of ammonium compounds in the soil is due mainly to their action. Moreover, certain bacteria govern the production of nitrates and sulfates, indispensable sources respectively of nitrogen and sulfur for higher plants.

In brief, without such microorganic activity, little simplification would occur. Nor would the solvent capacity of the soil water be increased to any degree by carbon dioxide. Also the generation of H-ions in the soil solution would practically cease and essential elements would become available to higher plants sparingly if at all.

1:14. CLAY AND HUMUS—THE SEAT OF SOIL ACTIVITY

It is now quite obvious that all normal soils are dynamic and changeable and that their markedly active constituents either are in a finely dispersed condition or are in contact with materials already in this state. In other words, most soil reactions, whether physical, chemical, or biological, de-

pend in large degree on the colloidal nature of certain major constituents, both living and nonliving.

Clay and humus, more or less intimately mixed, constitute most of the colloidal matter found in soils. These finely divided fractions not only promote the activity of other substances (catalysis) but also may themselves be permanently changed. In fact, humus may react and be reacted upon to the extent that it actually undergoes complete oxidation and thus disappears.

Adsorption, plasticity, cohesion, and certain chemical exchanges are all controlled by substances in the colloidal state. In truth, very few reactions occur in the soil that are not connected in some way with matter in this condition. While the humic colloids are the more active, pound for pound, the presence usually of a larger amount of viscous, gelatinous, and more stable clayey matter preserves a balance in their relative importance. The two, existing in the soil in the most intimate contact, function with surprising intensity and rapidity.

1:15. THE VIEWPOINT—A COLLOIDO-BIOLOGICAL CONCEPT

In any study of the soil, the importance of the colloidal state of matter obviously cannot be ignored. Nor can one escape certain conclusions regarding the significance of the soil organisms. In fact, a *colloido-biological* approach must be made to most soil problems whether technical or practical in nature.

Enlarging on such a conception, the soil may be visualized as possessing a framework of mineral matter—in part noncolloidal and inert; in part colloidal and extremely active. In mineral soils clayey materials make up much of this latter fraction. But in the surface layers of most soils there is mixed with this viscous, gelatinous mineral matter appreciable amounts of humus, notably colloidal and characteristically unstable. These two adsorptive and dynamic gels practically dominate the situation in both physical and chemical ways.

Clinging to the surfaces of this organo-mineral filling and imbedded in its gelatinous, porous depths live a vigorous fauna and flora, profuse, diverse, and persistent. This life, multiplying and dying, active and dormant by turn, draws most of its energy from the soil organic matter and brings about changes and reactions, not inherent in lifeless colloidal matter. Through and around this activated mineral and organic mass cir-

culate the air and water of the soil, augmenting or retarding the vital phenomena as the case may be.

Higher plants complete and strengthen this colloido-biological conception. As their rootlets penetrate the soil, forcing their way into the pore spaces and through the gelatinous fillings, the contacts between the root hairs and the soil colloidal matter become very close. (See Fig. 5:4.) In fact, so intimate are the colloidal associations that the plant really becomes a part of the soil system.

Simple as is this generalization, an inquiry into the details of such a complicated system is fraught with difficulties. The complexity of the various components of the soil, the instability of the humic constituents, and the bewildering succession of life with its enzymic complications make interpretation both difficult and uncertain. It is easy to see, therefore, why the development of soil science has been slow. And why the principles and practices cited on the following pages should be understood thoroughly if trustworthy decisions in respect to practical problems are to be made.

CHAPTER 2

The Supply and Availability of Plant Nutrients in Mineral Soils

THE FEATURE that early attracts practical attention is the capacity of soils to supply higher plants with certain essential elements. This is the fundamental problem in crop production. Hence, any sound concept of the interrelationships of soils and plants requires at the outset some knowledge of the necessary elements as they exist and function in soils. In undertaking such an examination, however, it is well to note that the consideration is not a simple one, partly because the growth of higher plants depends on at least six factors of which the essential nutrient elements make up one. Preliminary to a study of soil nutrients these six growth factors are briefly disposed of in the following section.

2:1. FACTORS CONTROLLING THE GROWTH OF HIGHER PLANTS[1]

The growth and development of higher plants depends on two sets of factors, the internal and the external. The latter group, of special interest from the soil standpoint, may be enumerated as follows: (1) light, (2) mechanical support, (3) heat, (4) air, (5) water, and (6) nutrients. With the exception of light, the soil is an agent in supplying, either wholly or in part these essential conditions.[2]

The two prime functions of the soil in respect to plants are realized through the proper coordination of the six factors mentioned above—suitable physical support and a sufficient supply of certain essential ele-

[1] For an excellent discussion of these factors, see Russell, E. J., *Soil Conditions and Plant Growth*, Longmans, Green and Company, New York, 1937, Chap. 2, pp. 32–57.

[2] Absence of disease and lack of serious insect pests are often mentioned as negative factors in this connection.

ments. For the present, the consideration of the first of these—the physical nature of the soil—will be passed over in order to present certain fundamentals in respect to plant nutrition.

2:2. THE ESSENTIAL ELEMENTS [3]

For the normal growth of both higher plants and microorganisms two conditions respecting the nutrients are vitally important. First, certain elements must be present and available for the use of the plant; and second, their concentration, especially in comparison with that of other essential nutrients, must be adjusted properly. The presence of too large an amount of one element may be as detrimental as an actual lack of this same constituent. Again the failure of the plant to utilize one element suitably may be due to an over- or undersupply of another.[4] Physiological balance is one of the important objectives of sound fertilizer practice.

Certain elements are, therefore, considered as especially desirable for successful crop growth. If they are lacking or improperly balanced, normal development does not occur. Fourteen such elements have been so recognized and their necessity can readily be demonstrated. They are listed in Table 2:1 and are classified according to sources—whether primarily from air and water or from soil solids—and whether used by plants in relatively large or small amounts.[5]

Table 2:1. Essential Nutrient Elements and Their Sources

Essential Elements Used in Relatively Large Amounts			*Essential Elements Used in Relatively Small Amounts* [6]	
Mostly from Air and Water	*From Soil Solids*		*From Soil Solids*	
Carbon	Nitrogen	Calcium	Iron	Copper
Hydrogen	Phosphorus	Magnesium	Manganese	Zinc
Oxygen	Potassium	Sulfur	Boron	

[3] For a rather extended discussion of the essential elements, see Russell, E. J., and E. W. Russell, *Soil Conditions and Plant Growth,* Longmans, Green and Company, New York, 1950, pp. 30–56.

[4] Too much nitrogen, for example, in proportion to the phosphorus available to plants, may encourage undesirable physiological conditions. Also too much calcium may interfere with phosphorus and boron nutrition or may encourage chlorosis due to a reduction in the availability of the soil iron, zinc, or manganese. The importance of a balanced nutrient ration in the soil and the difficulties of attainment in practice are dealt with on page 496.

[5] For instance it is not uncommon for a crop such as corn to remove 100 pounds

2:3. ESSENTIAL ELEMENTS FROM AIR AND WATER

Higher plants obtain most of their carbon and oxygen directly from the air by photosynthesis.[7] The hydrogen is derived, either directly or indirectly, from the water of the soil. All of the other essential elements, except certain supplies of the nitrogen acquired from the soil air indirectly by legumes,[8] are obtained from the soil solids.

It must not be inferred from this that the bulk of the plant tissue is synthesized from the soil nutrients. Quite the reverse is true. Ordinarily from 94 to 99.5 per cent of fresh plant tissue is made up of carbon, hydrogen, and oxygen, and only from 0.5 to perhaps 5 or 6 per cent is from soil constituents. In spite of this, it is the nutrient elements obtained from the soil that usually limit crop development. Plant growth, except in cases of drought, cold weather, poor drainage, or disease, is not seriously

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of nitrogen an acre. The amount of boron carried away by the same crop might be as little as 10 or 15 grams per acre.

[6] Other minor elements such as sodium, molybdenum, chlorine, fluorine, iodine, silicon, cobalt, strontium, and barium do not seem to be universally essential, as are the fourteen already cited, although the soluble compounds of some may increase crop growth.

The case perhaps is strongest for sodium. It has been known for years that this element will in part replace potassium and that common salt will at times increase crop yield. Such seems to be the situation with respect to mangels, sugar beets, Swiss chard, table beets, celery, and turnips grown on peat soils. That sodium is essential with certain crops under certain conditions is highly probable. This cannot be said with such confidence in respect to the other elements cited.—See: Lehr, J. J., "The Importance of Sodium for Plant Nutrition: II. Effect on Beets of the Secondary Ions in Nitrate Fertilizers," *Soil Sci.*, 52: 373–379, 1941; and Harmer, Paul M., and Erwin J. Benne, "Sodium as a Crop Nutrient," *Soil Sci.*, 60: 137–148, 1945.

For an extended bibliography, see, *Bibliography of References to the Literature on the Minor Elements and Their Relation to the Science of Plant Nutrition*, Fourth Ed., Vol. 1, 1948, Chilean Nitrate Educational Bureau, Inc., New York.

[7] In the process of photosynthesis, energy from the sun in the presence of chlorophyll, facilitates the synthesis of sugar from CO_2 and water, the former entering the plant through the stomata, the latter being absorbed from the soil. Formaldehyde and oxygen are thought to be intermediate products, the former probably being polymerized into hexose sugar. In keeping with modern concepts the synthesis may be indicated chemically as follows:

$$CO_2 + H_2O + \text{Light (in presence of chlorophyll)} \rightarrow CH_2O + O_2$$
$$6CH_2O \rightarrow C_6H_{12}O_6 \text{ (Sugar)}$$

According to the latest hypothesis, all of the oxygen as well as all of the carbon acquired by photosynthesis comes from CO_2, while the oxygen given off is evolved exclusively from water. See VanNiel, C. B., "The Comparative Biochemistry of Photosynthesis," *Amer. Scientist*, 37: 371–383, 1949.

[8] See page 458 for an explanation of this phase of nutrient acquisition.

retarded by a lack of carbon, hydrogen, and oxygen.[9] Hence, the nutritional emphasis that is placed on the soil and the eleven elements that it supplies.

2:4. ESSENTIAL ELEMENTS FROM THE SOIL

Primary elements. Of the eleven essential elements obtained from the soil by plants, six are used in relatively large quantities and consequently have and still are receiving, except in certain cases, major attention.[10] They are *nitrogen, phosphorus, potassium, calcium, magnesium,* and *sulfur.* Because they are used by plants in relatively large amounts they are sometimes designated for convenience as the *primary* elements. Plant growth may be retarded because these elements are actually lacking in the soil, because they become available too slowly, or because they are not adequately balanced by other nutrients. Sometimes all three of these limitations are operative. This is very often true in respect to nitrogen.

When nitrogen, phosphorus, and potassium are artificially supplied to the soil, they are usually added as farm manure and especially as commercial fertilizers. Therefore, they are often called *fertilizer* elements. In the same way calcium and magnesium are commonly applied as lime and are styled *lime* elements. Sulfur, other than that present in rain water, usually goes into the soil as an incidental ingredient of such fertilizers as farm manure, superphosphate, and sulfate of ammonia. Its addition, nevertheless, is very important in any scheme of fertility management. In special cases, sulfur is applied alone as flowers of sulfur, either to correct nutritional deficiencies or to adjust the reaction of the soil.[11]

Trace elements. The other nutrient elements (iron, manganese, copper, zinc and boron) are used by higher plants in very small amounts and as a consequence are sometimes called *trace* elements.[12] Such a designation does not mean that they are less essential than the so-called primary elements. In fact, such elements are fundamentally just as important (see Fig. 2:1).

[9] It is well to remember, however, that a serious lack of oxygen for roots may occur in heavy soils, especially if drainage is poor. This is an important factor in respect to the location of orchards, and is more critical than generally supposed. See page 281.

[10] In some places the *trace* elements are temporarily critical, but once the deficiency is met, the major fertilizer emphasis swings back again to the *primary* nutrients.

[11] For instance, certain regions in eastern Washington and Oregon are notably deficient in sulfur if alfalfa is to be grown successfully. Sulfur deficient areas also occur in Minnesota and elsewhere in the United States. For more regarding sulfur see pages 156 and 508.

[12] The terms *secondary, minor, micro,* and *rarer* are also used in referring to the elements needed in such small amounts by plants.

Fertilizer manufacturers sometimes place small amounts of these elements,[13] especially boron, in ordinary commercial fertilizers as an insurance against their possible lack or unavailability in the soil. This wholesale method, however, is rather haphazard unless large areas of soil, uniformly deficient, are to be fertilized. If there is any serious deficiency, it usually is advisable to add the salt of the limiting element separately to the soil. The recommendation made by the fertilizer expert can thereby be more accurately followed and over-applications avoided. In the case of trace elements it must always be remembered that the rate of application per acre is small and that the range between optimum additions and serious toxicity is narrow.[14]

FIG. 2:1. *Trace elements are just as necessary for normal plant growth as are nitrogen, phosphorus, and potassium. Note the influence of boron on sunflowers growing on a sand originally deficient in this constituent. The soil at the left received no boron. The progressive increase in plant growth to the right is in response to increasing increments of this element. Yet the maximum amount of boron applied was at the rate of only 2.4 pounds per acre furrow-slice. (Photo courtesy J. E. Dawson and Collin McClung.)*

Except for iron, trace elements are found sparingly in most soils.[15] Consequently, even though the removal by plants is small for any given season,

[13] Iron, manganese, copper, and zinc commonly are applied as sulfates—that is as $FeSO_4$, $MnSO_4$, $CuSO_4$ and $ZnSO_4$. Borax ($Na_2B_4O_7$) is used as the carrier of boron.

[14] Even under natural conditions these elements sometimes occur in toxic amounts as is the case of manganese in some Hawaiian soils and zinc in New York woody peats. Zinc from smelter smoke is a good example of commercial contamination.

[15] The following data give some idea as to the trace element content of representative surface soils of the United States and the ranges in composition that can be

the cumulative effects of crop production over a period of years may rapidly reduce the limited stores originally present. As a result, the so-called trace elements have become a pressing problem on many of the soils of the United States.

Certain deficiency symptoms once ascribed to other causes are now definitely known to be due to a lack of one or more of the trace elements.[16] Once the deficiency is accurately diagnosed, however, one or perhaps two applications, except for very sandy soils, often alleviates the difficulty for a number of years. The attention then, of course, shifts back to the primary nutrient elements which are used by plants in comparatively large amounts and which demand more constant and intense consideration. As a group they present a perennial fertility problem.

Four nutrient questions. In order to arrive at a logical conclusion as to why nutrient deficiencies often occur in soils, four phases of great importance must be examined. They are (1) the amounts of the various primary elements present in mineral soils, (2) their forms of combination, (3) the processes by which availability normally becomes possible, and (4) the soil solution and its pH. These phases will be considered in order.

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expected. These figures deal with totals, however, and throw no light on plant availabilities.

Nutrient	*Normal Range* [a] %	*Suggested Analysis of a Representative Surface Soil* %
Iron	.500–5.000 [b]	2.500
Manganese	.100–1.000 [c]	.250
Zinc	.003– .008 [c]	.005
Boron	.003– .008 [c]	.005
Copper	.001– .005 [c]	.003

[a] It is understood, of course, that some soils will fall outside of the ranges suggested.

[b] Based on a large number of total analyses. For data on specific soils see footnote table, page 26.

[c] From Allison, R. V. and L. W. Gaddum, "The Trace Element Content of Some Important Soils—A Comparison," *Proc. Soil Sci. Soc. Fla.*, 2: 68–91, 1940. Fifty-four Florida soils were examined as well as eleven representative soils from other parts of the United States. See also: Holmes, R. S., "Copper and Zinc Contents of Certain United States Soils," *Soil Sci.*, 56: 359–370, 1943.

[16] Copper, manganese, and zinc deficiencies are now of common occurrence in the citrus areas both in Florida and California. And with other crops growing on mineral soils, the lack of these nutrients, as well as of boron, is becoming more and more noticeable. Cases are now reported from all parts of the United States. A boron deficiency for apple trees, alfalfa, and cauliflower in eastern United States are cases in point. Both boron deficiency and boron toxicity are reported on the lighter soils of eastern Oregon. The situation on peat soils is just as urgent. Certain low moor soils of Florida respond to copper, manganese, and zinc, while a copper deficiency for lettuce and onions is common in New York woody peats.

2:5. AMOUNTS OF THE PRIMARY NUTRIENT ELEMENTS PRESENT IN MINERAL SOILS

Although soils vary greatly in chemical composition, it is possible to indicate the percentage range within which the primary nutrients are ordinarily found when a number of surface soils is considered. Also analyses are suggested for representative surface soils of humid-temperate and arid-temperate regions respectively. (See Table 2:2 and Fig. 2:2.)

Table 2:2. Total Amounts of Organic Matter and Primary Nutrients Present in Temperate-region Mineral Surface Soils [17]

Constituents	*Ranges in Percentages that Ordinarily May be Expected*[18]	*Representative Analyses* — *Humid Region Soil*		*Arid Region Soil*	
		Percentage	*Lb. to Acre Furrow-Slice*	*Percentage*	*Lb. to Acre Furrow-Slice*[19]
Organic matter	0.40–10.00	4.00	80,000	3.25	65,000
Nitrogen (N)	0.02– 0.50	.15	3,000	.12	2,400
Phosphoric acid (P_2O_5)	0.02– 0.40	.10	2,000	.15	3,000
Potash (K_2O)	0.20– 4.00	2.00	40,000	2.40	48,000
Lime (CaO)	0.10– 5.00	.60	12,000	1.50	30,000
Magnesia (MgO)	0.20– 2.50	.50	10,000	1.00	20,000
Sulfur trioxide (SO_3)	0.02– 0.50	.10	2,000	.20	4,000

[17] As a supplement to the generalized figures of Table 2:2, the analyses of eight representative United States surface soils are presented below as published by C. F. Marbut. For the complete set, see "Soils of the United States," *Atlas of American Agriculture*, Part 3, U. S. Dept. of Agriculture, 1935.

Constituents	*Norfolk Fine Sand, Florida*	*Sassafras Sandy Loam, Virginia*	*Ontario Loam, New York*	*Loam from Ely, Nevada*	*Hagerstown Silt Loam, Tennessee*	*Cascade Silt Loam, Oregon*	*Marshall Silt Loam, Iowa*	*Summit Clay from Kansas*
	%	%	%	%	%	%	%	%
SiO_2	91.49	85.96	76.54	61.69	73.11	70.40	72.63	71.60
TiO_2	0.50	0.59	0.64	0.47	1.05	1.08	0.63	0.81
Fe_2O_3	1.75	1.74	3.43	3.87	6.12	3.90	3.14	3.56
Al_2O_3	4.51	6.26	9.38	13.77	8.30	13.14	12.03	11.45
MnO	0.007	0.04	0.08	0.12	0.44	0.07	0.10	0.06
CaO	0.01	0.40	0.80	5.48	0.37	1.78	0.79	0.97
MgO	0.02	0.36	0.75	2.60	0.45	0.97	0.82	0.86
K_2O	0.16	1.54	1.95	2.90	0.91	2.11	2.23	2.42
Na_2O	Trace	0.58	1.04	1.47	0.20	1.98	1.36	1.04
P_2O_5	0.05	0.02	0.10	0.18	0.16	0.16	0.12	0.09
SO_3	0.05	0.07	0.08	0.12	0.07	0.21	0.12	0.11
Ignition	1.83	1.91	5.30	7.62	8.82	4.25	6.01	6.60
Nitrogen	0.02	0.02	0.16	0.10	0.27	0.08	0.17	0.09

AG57

It must be remembered, however, that such figures do not fit any particular soil, but present a very rough average of the data available. Also, it should be pointed out that the percentage values given are for topsoils only. These figures show that soils of arid regions are in general higher in all of the important constituents except organic matter and nitrogen. (See Fig. 2:2.) An exception, even to this, is found in the black earth soils

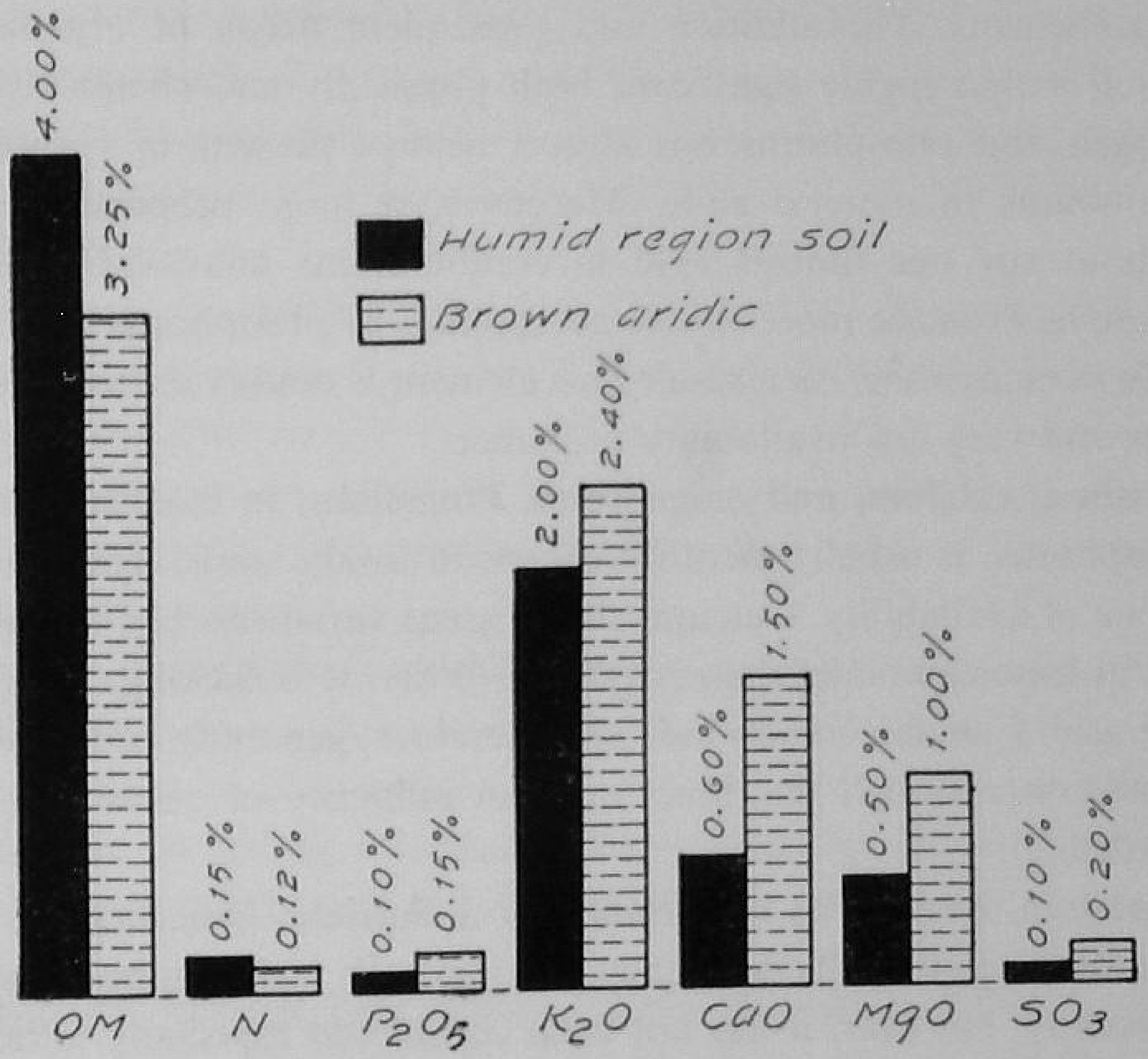

FIG. 2:2. *Chemical analyses of a representative humid region surface soil and a brown arid region surface soil respectively. Note in each case the relatively large amounts of organic matter and potash, the low percentages of nitrogen, phosphoric acid, and sulfur, and the intermediate rating of the lime and magnesia. Typical soils of arid regions, other than chernozems, seem in general to be higher in all of the constituents cited except organic matter and nitrogen.*

Note the variations in composition, especially in respect to the lime. Only one sample, that from Nevada, contains carbonates. It is an arid region soil. All of the others are from humid or subhumid areas. The ignition figure in no case is to be taken as an accurate measure of organic matter. It is usually too high.

18 Some soils will, of course, fall outside of these ranges in respect to one or more constituents.

19 The furrow-slice of a representative mineral soil is considered to contain approximately 2,000,000 pounds of dry earth to the acre.

(chernozems) of subhumid regions which sometimes may range as high as 16 per cent of organic matter and .70 to .80 per cent of nitrogen. (See page 349.)

Organic matter, nitrogen and phosphorus. The percentage of organic matter exceeds that of any other constituent listed in Table 2:2. Yet its amount in most surface soils usually is critical. It is of prime importance in keeping the soil loose and open and is an essential source of several nutrient elements. The addition and subsequent decay of organic matter in the soil is thus highly significant both physically and chemically.

Nitrogen and phosphorus are almost always present in comparatively small amounts in mineral soils. Moreover, a large proportion of these elements at any one time is held in combinations unavailable to plants. For example, even the more simple compounds of phosphorus are relatively insoluble in many soils. As a result, this element is doubly critical—low total amounts and very low availability to plants.

Potassium, calcium, and magnesium. Potassium, in marked contrast to the phosphorus, is usually plentiful except in sandy lands. The main problem is one of availability. Calcium shows great variations but it is generally present in lesser amounts than is potash. When it is lacking, soils tend to become acid. Calcium compounds are, therefore, generally added to correct this condition although the direct nutrient influence of calcium cannot be disregarded.

Magnesium, besides its importance as a nutrient, functions in the soil much as does calcium. Its deficiency in some soils has long been suspected. Until recently, however, it has not been considered especially critical since it is carried by most limestones, sometimes in large amounts. Where liming is practiced, therefore, its lack often is automatically rectified. In spite of this, however, magnesium deficiency is a major problem in many areas in eastern United States.[20]

Sulfur. While usually no more plentiful than phosphorus, sulfur is more readily available. This is because its simple inorganic compounds are not rendered insoluble by reacting with certain other soil constituents as is the

[20] Magnesium deficiencies are especially prevalent in the citrus areas of Florida and its lack has been observed throughout the Atlantic seaboard trucking districts from Florida to Maine. Nor are deficiency symptoms absent on such crops as corn and small grains over much of eastern and central United States. Since magnesium is carried by the chlorophyll molecule, any lack is immediately registered by a characteristic chlorosis of the foliage of plants. For publications descriptive of deficiency symptoms see citations at bottom of page 486.

case with phosphorus. As already suggested, the addition of sulfur in farm manure, rain water, and in fertilizers, tends in an automatic way to relieve a possible deficiency in humid-temperate regions. In certain areas of the west, however, specific additions of sulfur containing compounds are required.

Critical constituents. The above discussion seems to indicate that three constitutents are likely to be critical in almost all mineral soils. Two—*organic matter* and *nitrogen*—merit particular attention because of the small amounts originally present and because of their ready loss through oxidation, leaching or crop removal. The third, *phosphorus,* faces a double handicap as already explained—an exceptionally small amount present and a surprisingly low availability to higher plants.

Under humid conditions *calcium* by all means must be included in the list above since it is sure to be much depleted by leaching. Consequently, it is needed not only as a nutrient but also as a means of controlling soil acidity. In arid regions, however, the leaching of calcium usually is negligible. Consequently, this nutrient is likely to be present in abundance, especially in the subsoil.

It is not to be inferred from the preceding generalizations, however, that *potassium, magnesium,* and *sulfur* may not be lacking in certain soils or that the problem of their supply may not at times be critical. The ever-increasing use of potash fertilizers, the demand for dolomitic limestone, and the emphasis placed on sulfur additions are evidence of this.

2:6. FORMS IN WHICH THE PRIMARY NUTRIENTS OCCUR IN SOILS

An examination of representative soils will reveal that in general the nutrient elements exist in two conditions: (1) complex and rather insoluble forms and (2) simple compounds usually soluble in the soil water and rather readily available to higher plants. Due to the chemical and biochemical processes at work the general trend of the elements in the soil is from the complex to the simpler forms. (See Table 2:3.) Thus, the nutritional needs of higher plants are served as soil evolution progresses.

This does not mean, as a person might hastily assume, that the reverse process, that of synthesis and increased complexity, does not normally occur in soils. In fact, such reactions are continually taking place and in many cases are of tremendous practical importance. The building of amino acids and proteins from nitrogen, nitrates, and ammonium compounds and the reversion of soluble phosphates to complex and insoluble forms are

good illustrations of such reversibility. The fixation of potassium by soils, and the tying-up of iron, manganese, and zinc by a rise in soil pH may also be cited.

Simple available forms. The simpler and more soluble constituents of soils, especially those of humid regions, readily disappear in drainage or are used by microorganisms and higher plants. Consequently, the greater proportion of the various nutrients exists in the soil at any one time in complex conditions. From thence they gradually become available through various processes of simplification. As a result, the productive capacity of a soil depends not so much upon the total amounts of the various nutrients present as upon the ease with which transfer is made to simple and available forms. Such a situation indicates why a total chemical analysis is likely to be of uncertain value in deciding what the fertilizer needs of a soil may be. This is rather discouraging as the total amount of a nutrient may be determined with great accuracy while its availability ordinarily is susceptible to little more than a rough approximation.

Organic combinations. Usually the rapid decomposition of the soil organic matter allows nutrients held in this complex form to be released and simple compounds appear which are more or less available to higher plants. Practically all of the nitrogen and in some surface soils, a large proportion of the sulfur and the phosphorus [21] are held in organic combinations. (See Table 2:3.) Since phosphorus in complex mineral forms usually is very slowly available, there is some advantage of the organic association. Even so, however, organic phosphorus does not become available as easily and quickly as do organic sulfur and nitrogen.[22]

Inorganic combinations. Most of the potassium, calcium and magnesium exists in the soil in strictly inorganic forms. There is quite a difference, however, in the degree of availability of the three elements.[23] For example,

[21] The proportion of the total phosphorus in the organic form may vary from about 20 to 75 per cent. See Table 17:1 page 474.

[22] It is well established that some of the organic phosphorus compounds such as phytin and nucleic acids react with clays forming very complex phytates and nucleates. These compounds apparently markedly resist microbial mineralization. This "frozen assets" concept helps explain why crops growing on soils high in organic matter and phosphorus sometimes exhibit phosphorus deficiency symptoms. See: Pierre, W. H., "The Phosphorus Cycle and Soil Fertility," *Jour. Amer. Soc. Agron.*, 40: 1–14, 1948.

[23] In humid-region mineral surface soils the amount of calcium in an exchangeable form usually is ten to twelve times greater than the adsorbed potassium and three to five times in excess of the exchangeable magnesium. Moreover, sometimes as much as 50 per cent of the total soil calcium may be exchangeable, although 20 to 25 per cent is more usual. One per cent ordinarily is a fairly high corresponding figure

Table 2:3. Forms in Which the Primary Nutrient Elements Occur in Mineral Soils[24]

Group 1 *The More Complex and Less Active Forms*	Group 2 *Some of the Simpler and More Available Forms and Their Ionic Equivalents*	
Nitrogen		
Organic combinations: proteins, amino acids, and similar forms; colloidal and subject to decomposition.	Ammonium salts.	NH_4^+
	Nitrite salts.	NO_2^-
	Nitrate salts.	NO_3^-
Phosphorus		
Apatite, an original source. Secondary Ca, Fe, Al phosphates. Organic; phytin and nucleic acid combinations.	Phosphate of Ca, K, Mg, etc. . . Soluble organic forms.	$PO_4^{\equiv}$ $HPO_4^=$ $H_2PO_4^-$
Potassium		
Original minerals such as feldspars and mica. Complex secondary aluminum silicates such as clays, especially illite.	Potassium ions adsorbed by colloidal complex. Potassium salts, such as sulfates, carbonates, etc.	K^+
Calcium		
Original minerals such as feldspars, hornblende, calcite and dolomite. Secondary aluminum silicates, especially clays.	Calcium ions adsorbed by colloidal complex. A variety of simple calcium salts.	Ca^{++}
Magnesium		
Minerals such as mica, hornblende, dolomite, and serpentine. Secondary aluminum silicates, such as clays, especially montmorillonite.	Magnesium ions adsorbed by colloidal complex. Numerous simple salts of magnesium.	Mg^{++}
Sulfur		
Mineral combinations such as pyrite and gypsum. Organic forms; colloidal and subject to decomposition.	Various sulfites . . . . and sulfates . . . . of Ca, K, Mg, etc.	$SO_3^=$ $SO_4^=$

a much larger amount of calcium is held in an easily replaceable condition by the colloidal complexes. (See Fig. 2:3.) In fact, the quantity of

for potassium. A reasonable estimate as to the proportion of the total magnesium in an exchangeable form is 6 or 7 per cent. The situation is shown graphically by Fig. 2:3.

[24] It is exceedingly important to note at the outset that a very large proportion of each plant nutrient is held in complex combinations (Group 1), simple and easily available forms (Group 2) being sparingly present in most cases.

this element in a replaceable or available form far exceeds that of any other metal in the soil. This is reflected in the copious losses of calcium in drainage water and the consequent need for its replacement by liming.

The situation in respect to potassium, and to a lesser extent for magnesium, is quite different. A very high percentage of the total quantities of these elements are held in the less available forms. (See Fig. 2:3) The exchangeable or readily available potassium, for example, usually makes up less than 1 per cent of the total quantity of this element in the soil. Although the content of exchangeable magnesium is usually somewhat higher, it is still much lower than that of calcium.

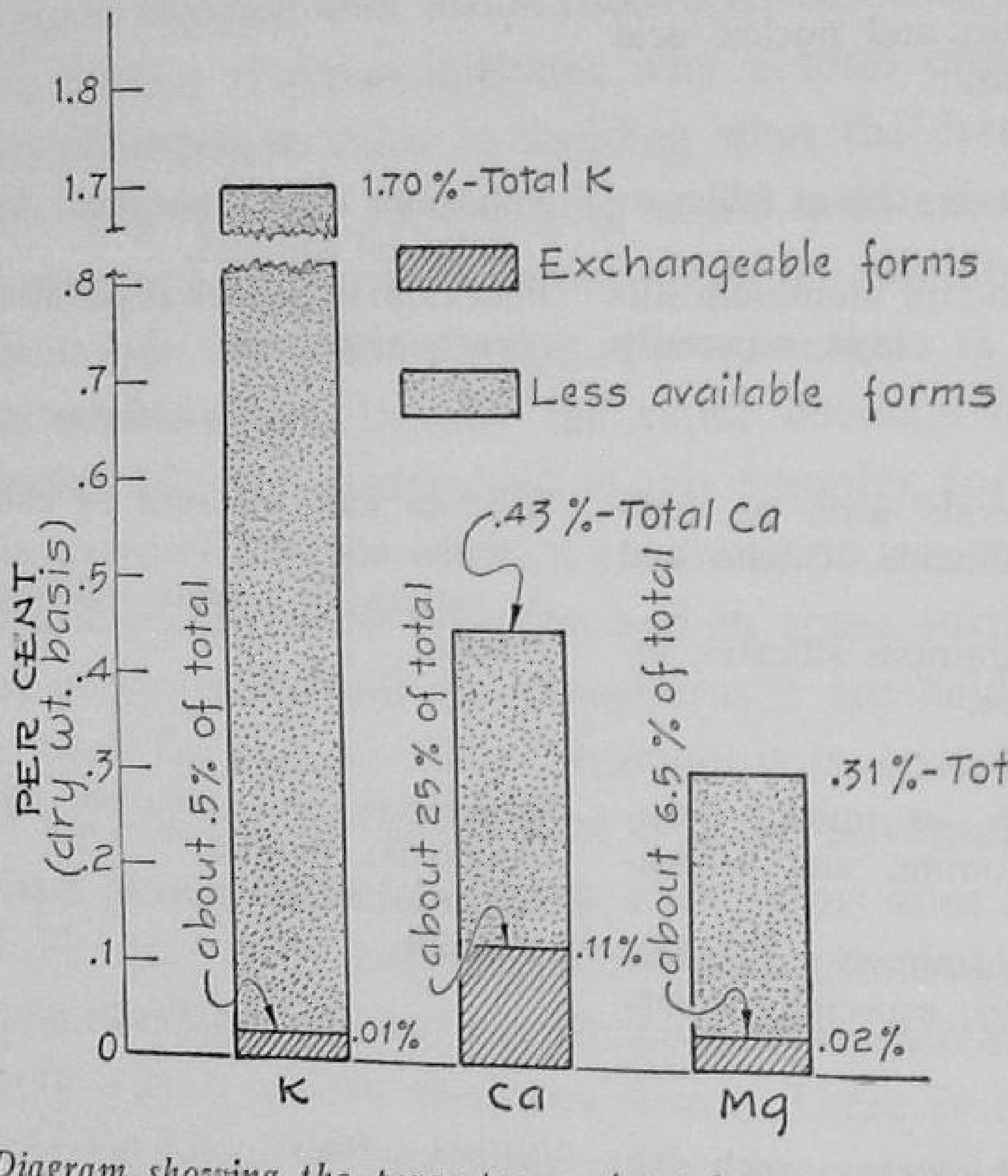

FIG. 2:3. *Diagram showing the percentages of total and exchangeable K, Ca, and Mg respectively present in the representative humid-temperate region mineral soil. Note that the amount of exchangeable Ca is approximately 10 times greater than the exchangeable K and 5 times that of the exchangeable Mg. About 25 per cent of the total Ca is represented as exchangeable, the corresponding figures for K and Mg are .50 per cent and 6.50 per cent, respectively. See note on page 30.*

While sulfur is held in both mineral and organic forms (see Table 2:3), the latter combinations tend to predominate in humid-region surface soils, especially if the soil organic matter is properly maintained. The availability of sulfur depends on the rate of organic decomposition. Its transfer, when present in such soils in sufficient quantity, seldom, if ever, gives trouble.

In soils of arid regions considerable sulfur may occur in the sulfate form as well as in organic combination. Gypsum is a common carrier of inorganic sulfur in such soils. The presence of calcium sulfate in the lower horizons of the chestnut soils of the Dakotas is an example. (See page 350.)

2:7. THE TRANSFER OF PLANT NUTRIENTS TO AVAILABLE FORMS

The soil is such a complex body that it is impossible, at least at this point, to picture in any detail the various changes that normally occur. The discussion that follows can only indicate in a very general way some of the more important transformations which affect the availability of the essential elements. The productivity of the soil, of course, depends on the trend of these reactions.

Nitrogen. Since most of the soil nitrogen is found in the organic matter, the decomposition of the latter must take place in order that the nitrogen may appear in simple forms. This decomposition is a very complex, biochemical process, and is accompanied by the evolution of much carbon dioxide. The nitrogen finally emerges as an ammonium compound and, if conditions are favorable, it is oxidized to the nitrite and then to the nitrate form. The two latter changes are spoken of as *nitrification* and are brought about by two special-purpose bacterial groups. Since much of the nitrogen utilized by higher plants is absorbed in the ammonium and nitrate forms, the importance of these processes is obvious. The transformations[25] may be outlined in a simple way as follows:

Organic nitrogen (proteins, amino-acids, etc.)	⟶	Ammonium Salts NH_4^+	⟶	Nitrite Salts NO_2^-	⟶	Nitrate Salts NO_3^-
Decomposition and Ammonification				Nitrification		

Since the above transformations are largely due to the activity of the micro-flora, they are influenced profoundly by soil conditions. When the soil is cold or waterlogged, these biochemical changes do not progress rapidly. Again the lack of sufficient available calcium, allowing the soil to become acid, retards the processes. The nitrifying organisms are especially sensitive to both conditions.

[25] Further information regarding decomposition, ammonification, and nitrification is given on page 449 and ff.

When organic matter containing a large amount of carbon compared to nitrogen is added to a soil, the above processes are not only retarded but may temporarily be reversed. The soil microorganisms having large amounts of energy-producing materials at their disposal, multiply rapidly and use the nitrogen themselves, thus interfering with its simplification and appearance as ammonium and nitrates. In such cases, the soil flora is competing directly with the higher plants.[26] It must be concluded, therefore, that the simplification of the nitrogen is not always easy, rapid, or in proportion to the amounts present. This must, of course, be taken into consideration in the practical management of any soil.

Phosphorus. When the soil phosphorus is held in organic combination, decay will encourage its simplification. The mineral phosphorus, however, presents a much more difficult problem. The various native soil phosphates are usually rather insoluble.[27] Even when the normal solvent agent, carbonic acid, is present in relative large amounts, the rate of solution still is slow. The situation is made even more difficult by the small amounts of phosphorus present. A simple example illustrative of the solvent influence of carbon dioxide and water is given below, tricalcium phosphate [28] tentatively representing the various insoluble soil phosphates:

$$\underset{\text{Insoluble phosphate}}{Ca_3(PO_4)_2} + 4H_2O + 4CO_2 \longrightarrow \underset{\text{Water-soluble phosphate}}{Ca(H_2PO_4)_2} + \underset{\text{Soluble calcium bicarbonate}}{2Ca(HCO_3)_2}$$

Plant rootlets, aided by CO_2 and certain other exudates, promote the sort of transfer illustrated above. Crops may thereby encourage an availability that might otherwise be almost negligible. Thus a soil may be able to supply a crop with appreciable quantities of phosphorus, and yet its solution and drainage water may contain very small amounts of this element.

It should also be emphasized that this simplification, like that of the nitrogen, may be reversed. Microorganisms readily appropriate simple and soluble phosphorus compounds and build them up into complex organic forms. Again the addition to soils of such soluble fertilizer compounds as

[26] A full discussion of the carbon-nitrogen ratio and its practical significance will be found on pages 164 and 166.

[27] For a statement regarding the various soil phosphates and their relative availability, see page 473 and ff.

[28] It is questionable whether the simple tricalcium phosphate ($Ca_3(PO_4)_2$) actually exists in soils. It is used here merely in an illustrative way.

$Ca(H_2PO_4)_2$ and $NH_4H_2PO_4$ is usually attended by a reversion to insoluble calcium phosphates or to the equally complex and insoluble iron and aluminum combinations. Such forms liberate their phosphorus very reluctantly indeed.

Potassium and calcium. The potassium and calcium, held largely in mineral combination, must also succumb to the solvent action of water charged with carbon dioxide if they are to appear in the soil solution. There is a difference, however, in the manner by which these elements become available. Much of the potassium must first be released from a molecular or semi-molecular combination with the soil minerals. This is often difficult. A large proportion of the calcium, on the other hand is already in an exchangeable form from which it is easily released to the soil solution. The reactions that follow illustrate the processes, a potash feldspar representing the complex silicate compounds in which potassium is often found. The easily replaceable combinations of the calcium are indicated by a generalized formula that symbolizes the adsorbed[29] condition in which so much of it exists in soils.

$$2KAlSi_3O_8 + CO_2 + 2H_2O \longrightarrow H_4Al_2Si_2O_9 + K_2CO_3 + 4SiO_2$$

Microcline feldspar			Hydrated silicate	Soluble carbonate	

$$Ca\,\boxed{\text{Colloidal Surface}} + 2H_2CO_3 \longrightarrow \begin{matrix}H\\H\end{matrix}\boxed{\text{Colloidal Surface}} + Ca(HCO_3)_2$$

Adsorbed calcium	Carbonic acid	Adsorbed hydrogen	Soluble bicarbonate

Some of the potassium thus liberated remains in the soil solution to be used by plants or lost in drainage. Most of it, however, is adsorbed by the negatively charged colloidal surfaces. When so held it is less subject to loss by leaching but still is available to higher plants.

A great deal of the calcium becomes mobile, however, by a simple exchange of hydrogen ions for those of calcium. This replacement, or *ionic exchange* as it is called, takes place with surprising ease and rapidity, and

[29] *Adsorption* refers to the adhesion of substances to the surfaces of solids. In soils it has to do particularly with the concentration of molecules of water and of ions of various types at colloidal surfaces. Adsorption is an interface phenomenon.

Absorption in contrast refers to surface penetration such as takes place when nutrients and water enter plant roots. Thus Ca-ions, for instance, are *ab*sorbed as they are taken in by plant roots but *ad*sorbed by soil colloids.

undoubtedly is one of the most important types of reactions occurring in soils.[30] Because of this situation, soils, although containing in general considerably more potassium than calcium (see Table 2:2 and Fig. 2:2), liberate the latter element much more lavishly. (See Fig. 2:3.) This has a direct bearing on calcium nutrition, soil acidity, liming, and other practical considerations.[31]

Magnesium. Since magnesium is held in the soil in much the same condition as is calcium, the exchange reaction cited for the latter shows how the magnesium may be released to the soil solution. However, some of the magnesium no doubt comes directly from the soil minerals by hydrolysis and carbonation, much as does the potassium. Hence, the illustrations cited for the transfer of potassium and calcium will serve for magnesium also. It is only necessary to visualize the formation and solution of magnesium bicarbonate by hydrolysis and carbonation in one case and by ionic exchange in the other.

Just as in the case of nitrogen and phosphorus, the release of potassium, calcium, and magnesium to the soil solution may easily be reversed. Thus, when soluble compounds of potassium, calcium, or magnesium are added to a soil, the colloidal matter adsorbs large quantities of the metallic ions. Indeed, they may be even more firmly fixed as a molecular part of the clayey colloidal matter. This is especially true for potassium.

Sulfur. As in the case of the nitrogen, the sulfur transformations are largely biological. They go on readily in most soils and while probably subject to marked retardation at times, such influences are apparently not as serious as in the case of the nitrogen. The transformations may be indicated in a general way as follows:

Organic sulfur (Proteins and other organic combinations) ⟶ Decay products (Of which H_2S and other sulfides are simple examples) ⟶ Sulfites $\overset{=}{SO_3}$ ⟶ Sulfates $\overset{=}{SO_4}$

Decomposition of organic matter (Organic sulfur ⟶ Decay products) — Sulfur oxidation (Decay products ⟶ Sulfites ⟶ Sulfates)

The last stage, sulfur oxidation,[32] is, like nitrification, brought about largely by certain types of bacteria. The sulfate compounds that result (see

[30] The full significance of ionic exchange will be set forth later. See page 97 and ff.

[31] It should be mentioned at this point that the colloidal complex of the soil carries other cations besides calcium and hydrogen in a replaceable condition. Magnesium, potassium, ammonium, sodium, and other ions are present in minor amounts.

[32] More information regarding sulfur oxidation may be found on page 156.

Table 2:3) are the source of most of the sulfur acquired by higher plants.

Again, soil organisms, especially bacteria and fungi, utilize sulfur as well as the metals already mentioned. Their synthetic activities are excellent examples of a practical reversal of the simplifying processes. Such transpositions while they temporarily compete with higher plants, tend to conserve nutrients by reducing the loss of valuable constituents in drainage water.

2:8. MORE ABOUT THE SOIL SOLUTION—ITS pH

It has already been emphasized that the soil solution is not always continuous, due to its segregation in the large and small pore spaces of the soil. (See section 1:11 on page 14.) As a result not all of the water can move freely. Also the soil solution is exceedingly changeable, varying as to the gross amount present in any soil, as well as to the amount and proportion of its soluble constituents.

Concentration of soil solution. It is agreed in general that as the soil solution is reduced in amount, especially by evaporation, its concentration of soluble salts rises rapidly. Hence, if the moisture fluctuation in a humid-region mineral soil is of sufficient range, a variation from a few parts per million, say 100, to possibly 30,000 parts a million in the concentration of the soil solution is quite possible. But because of the heterogeneity of the solution and its constant fluctuation, it is difficult to suggest an average or normal concentration. Perhaps under ordinary conditions the acre-furrow-slice of an arable humid-region mineral soil contains from 500 to 1000 pounds of soluble salts.

In arid and semi-arid regions, the soil solution is usually much more concentrated than where the rainfall is heavier, so much so, indeed, as to interfere at times with the growth of plants. The presence of even 0.5 per cent of total soluble salts is considered serious. This would mean about 10,000 pounds to an acre-furrow-slice.

Reaction of the soil solution. Another point of importance in respect to the soil solution is its reaction—that is, whether it is *acid, neutral,* or *alkaline.* Without considering at this time the conditions controlling soil reaction (see page 391), it suffices to say that some soil solutions possess a preponderance of H- over OH-ions and, therefore, are acid. Some, on the other hand, show the reverse and are alkaline, while others having an equal concentration of H- and OH-ions, are neutral. (See Fig. 2:4.)

The exact relationship in any particular case is usually evaluated in terms of H-ion concentration which is usually expressed in terms of pH. A soil is said to be *acid* if the pH is less than 7, *neutral* if at 7 and *alkaline* if the pH is above 7. Thus as the H-ions of the soil solution increase the pH decreases and vice versa. On the other hand, as the OH-ion concentration increases the pH of the solution goes up accordingly.[33]

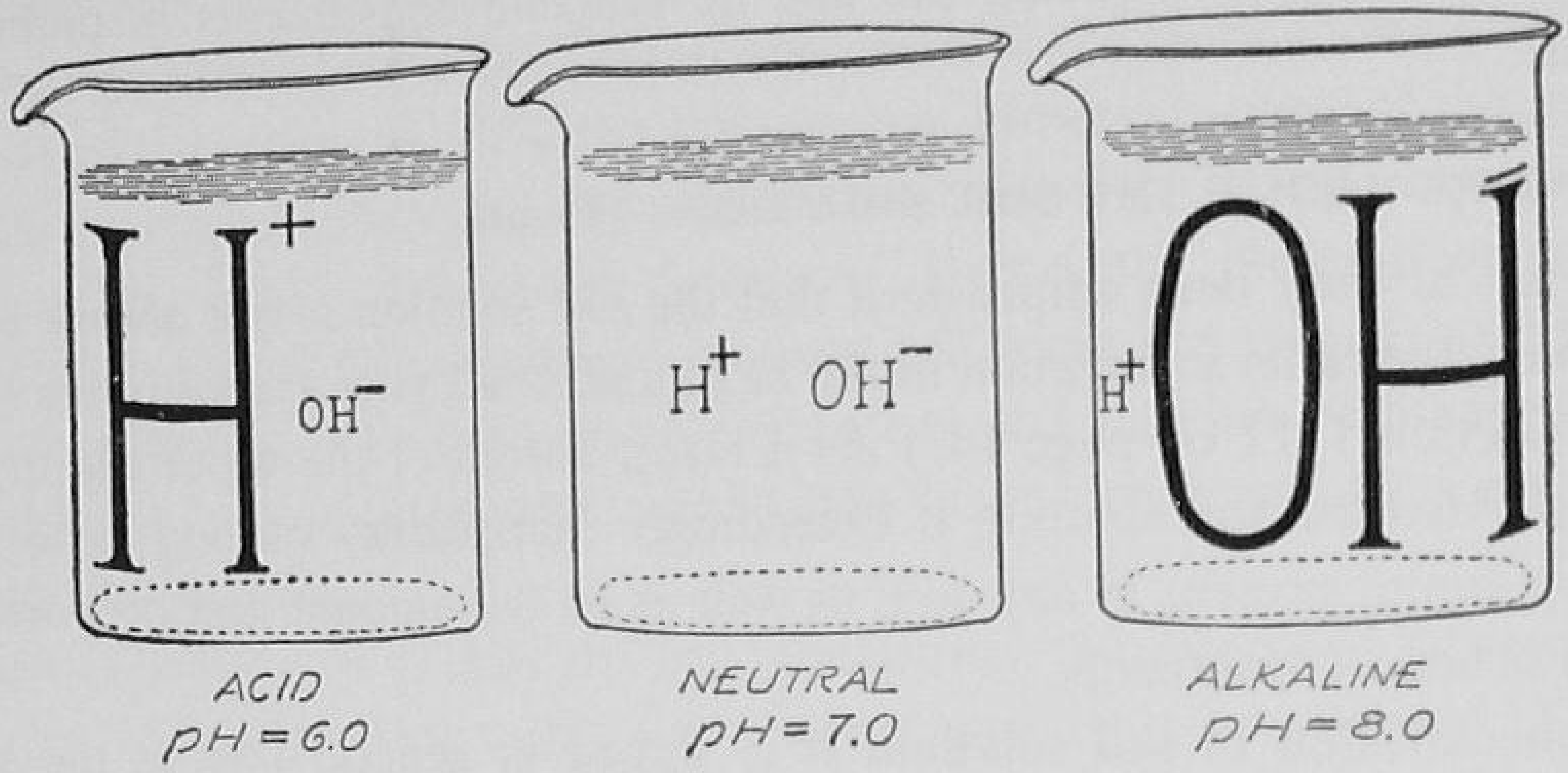

FIG. 2:4. *Diagrammatic representation of neutrality, acidity, and alkalinity. At neutrality the H-ions and OH-ions of a solution are balanced, their respective numbers being the same (pH 7).*

At pH6 the H-ions are dominant, being 10 times greater while the OH-ions have decreased proportionately being only 1/10 as numerous. The solution, therefore, is acid, there being 100 times more H-ions than OH-ions present.

At pH 8 the exact reverse is true, the OH-ions being 100 times more numerous than the H-ions. Hence the solution is alkaline. This mutually inverse relationship must always be kept in mind in using pH data. See note at bottom of page.

It is not to be inferred that we are dealing with a homogeneous distribution of the H- and OH-ions in the soil solution. Hydrogen ions usually are adsorbed by soils to a much greater degree than are the OH-ions. Consequently, one is prepared to visualize the H-ions as being especially concentrated at and near the colloidal interfaces and as becoming less numerous as the outer portions of the water films are approached. (See Fig. 14:1.) Since the OH-ions vary in numbers inversely with the H-ions, this makes for a higher pH in the outer moisture zones. As a result, the drainage water

[33] If the reader is not definitely familiar with pH values, it would be well to consult a good textbook on chemistry. It may be pointed out here, however, that the pH value of a solution is the logarithm of the reciprocal of the H-ion concentration. It may be stated conveniently as follows:

$$pH = \log \frac{1}{[H^+]}$$

from even a markedly acid soil may be only slightly acid or even neutral or alkaline due to this inverse relationship in respect to H- and OH-ions. Such a situation has many nutritional consequences in respect to both microorganisms and higher plants and will receive more attention later (pages 406 and 407).

From the practical standpoint, it is often necessary to interpret the pH of the soil solution in general and comparative terms. Figure 2:5 will be found helpful, not only in this respect, but also in visualizing the range in pH that ordinarily can be expected in soils.

Ranges in pH. Two types of pH ranges are shown in Figure 2:5, *extreme* and *common*. For mineral soils the extreme range in pH extends from near 3.5 to perhaps 10 or above. It is to be noted in this connection that

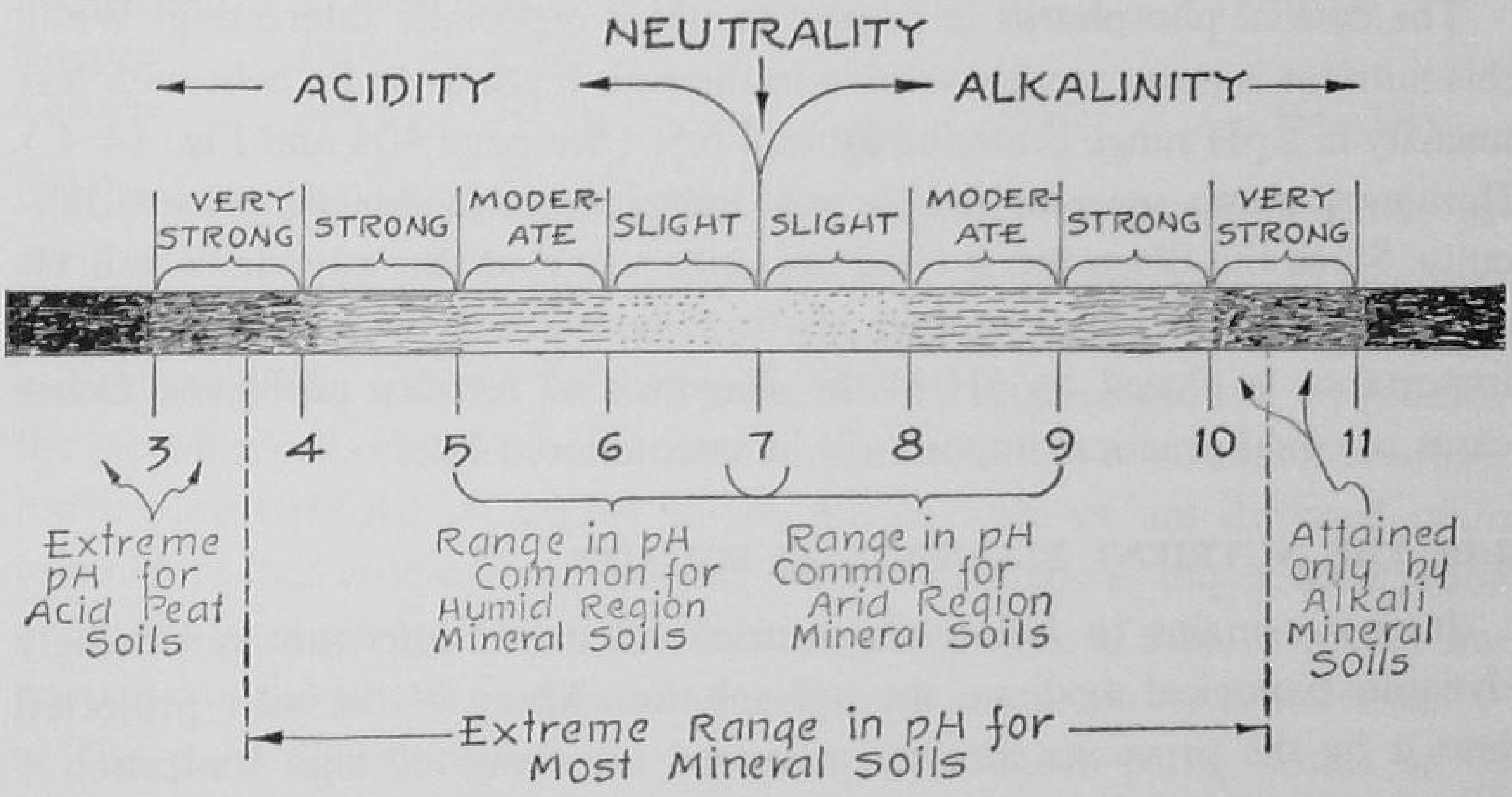

FIG. 2:5. *Diagram showing the extreme range in pH for most mineral soils and the range commonly found in humid regions and arid region soils respectively. The maximum alkalinity for alkali soils is also indicated, as well as the minimum pH likely to be encountered in very acid peat soils.*

certain peat soils may show a pH of less than 3. At the other extreme are alkali soils, some of which may reach a pH near 11.

The *common* ranges in pH shown by soils of humid regions and arid regions respectively are sharply in contrast with the extreme spread noted above. That for soils of humid regions extends roughly from somewhat below 5 to above 7. It is to be noted that the latter figure overlaps the range common to soils of arid regions whose usual pH spread is from a little below 7 to approximately 9.

2:9. THE NUTRITIONAL IMPORTANCE OF SOIL pH

To strengthen the inferences already made respecting the nutritional importance of soil pH, illustrations are in order. Hydrogen ions have considerable influence not only upon (1) the solubility of nutrients but also upon (2) the facility with which these nutrients, even when already in solution, are absorbed and used by plants. Iron, manganese, and zinc are excellent examples of the first relationship, as they tend to become less and less soluble as the pH rises, say from 4.5 to 7.5 or 8.0. The utilization of nitrate and ammoniacal nitrogen by plants is an excellent illustration of the second phenomenon. At a pH above 6.5 or 7, ammonium salts are thought to be utilized the more readily. But in moderately to strongly acid soils, nitrates apparently are absorbed with greater ease.[34]

The case of phosphorus in respect to pH is especially interesting. While this nutrient is never readily soluble in the soil, it seems to be held with less tenacity in a pH range centering around 6.5. (See page 404 and Fig. 14:4.) Here most plants seem to be able to extract it from the soil with least difficulty. Since the illustrations cited are only a few of the ways in which H- and OH-ions function physiologically in soils, it is easy to see why so much importance is placed on pH in the diagnosis of fertility problems. Other cases of equal practical import will be encountered later.

2:10. THE NUTRIENT ELEMENTS AS SOLUTES

It now remains to follow the nutrient elements into this surprisingly dynamic biological medium, the soil solution. Many of the salts projected into it by the processes already discussed are those of high ionization.[35] As a consequence, the soil solution is definitely ionic, the degree depending in a part on the concentration. When the solution is dilute, a very large proportion of the soluble constituents are present as ions. As the solution becomes more concentrated, during a dry spell for example, the proportion of the soluble substances in molecular association tends to increase. This latter condition, but much accentuated, holds true for arid-region soils also.

The soil nutrients are thus presented to the plant both in ionic and

[34] See Tiedjins, V. T., "Factors Affecting Accumulation of Ammonia and Nitrate Nitrogen, Particularly in Tomato and Apple," *Plant Physiol.*, 9: 31–57, 1934.

[35] According to the theory of electrolytic dissociation, many compounds when in solution exist as electrically charged portions called *ions*. For instance, KCl dissociates into K^+ and Cl^- ions while $NaNO_3$ yields Na^+ and NO_3^-. Many electrolytes when in dilute concentration ionize almost completely. The degree of dissociation is in general greater for inorganic salts than for those organic.

molecular forms, the proportions depending on conditions. In an arable soil, especially that of a humid region, the ionic intake is thought to predominate, not only because of the nature of the soil solution, but also probably because of the greater ease with which the ions penetrate the absorbing tissues. Knowing the soluble salts that commonly enter the soil water, it is easy to postulate the nutrient ions that come in contact with the absorbing tissues of microorganisms and higher plants. They may be tabulated as follows:

Nitrogen	NH_4^+,	NO_2^-, NO_3^-	Calcium	Ca^{++}
Phosphorus	$PO_4^{\equiv}$,	$HPO_4^{=}$, $H_2PO_4^-$	Magnesium	Mg^{++}
Potassium	K^+		Sulfur	$SO_3^{=}$, $SO_4^{=}$
Iron	Fe^{++},	Fe^{+++}	Zinc	Zn^{++}
Manganese	Mn^{++},	Mn^{++++}	Boron	$BO_3^{\equiv}$
Copper	Cu^+,	Cu^{++}		
Carbon	$CO_3^{=}$,	HCO_3^-	Water	H^+, OH^-

Nitrogen, phosphorus and sulfur. An explanation should be made regarding the use by plants of certain ions. Most of the nitrogen, for example, is absorbed in either the ammoniacal or nitrate forms, depending on the conditions of the soil, the kind of plant, and its stage of growth. In general, the presence of both ions seems most favorable. When nitrification is active, nitrites are oxidized so readily to the nitrate form or are disposed of in other ways that little can accumulate. This is fortunate as any concentration of nitrite nitrogen is likely to be toxic to plants. Here, then, is a very important ion but one that does not function to any extent as a nutrient.

The particular phosphate ion presented to higher plants seems to be determined to a considerable extent by the pH of the soil. When the latter is distinctly alkaline, the PO_4-ion apparently predominates in the soil solution. As the pH is lowered and the soil becomes slightly to moderately acid, the HPO_4- and H_2PO_4-ions prevail, while at high acidities the phosphorus is present largely as H_2PO_4-ion. All of these forms are considered to be absorbed by higher plants. It is well to note that soluble organic forms of phosphorus, although they seem to predominate in many soil solutions,[36] cannot be used to any extent directly by higher plants but must undergo mineralization and appear in the ionic forms already indicated before appreciable utilization takes place.

[36] Pierre, W. H., and F. W. Parker, "Soil Phosphorus Studies: II. The Concentration of Organic and Inorganic Phosphorus in the Soil Solution and Soil Extracts and the Availability of the Organic Phosphorus to Plants," *Soil Sci.*, 24: 119–128, 1927.

The intake of sulfur by higher plants apparently is largely as the SO_4-ion. This is the final product of oxidation and if the sulfur organisms are vigorous, little SO_3-ions can accumulate. The situation in some respects resembles that already cited regarding nitrification.

Other elements. Little need be said at this point regarding potassium, calcium, magnesium, zinc, and boron as they occur in the soil solution in only one ionic form respectively. But iron, manganese, and copper are in a little different category. The oxidation-reduction condition of the soil is a factor here. If the soil is well aerated, the ion of higher valence in each case tends to predominate. But if drainage is poor, reduction may occur and the lower valent ionic forms will be present.[37] Thus aeration, especially in the subsoil, is of tremendous nutritive importance.

The carbon dioxide of the atmosphere in its photosynthetic role is the direct source of most of the carbon acquired by higher plants, but not necessarily of all. In the soil solution carbonates and bicarbonates occur in abundance, which, when dissociation occurs, develop CO_3- and HCO_3-ions. If these are absorbed by higher plants, and there seems no reason why they should not be, carbon might be thus acquired. In fact, at times a considerable amount of carbon probably enters the plant directly from the soil.[38]

While most of the water absorbed by higher plants goes to offset transpiration losses (see page 220), some is used to satisfy the nutritional needs for hydrogen and perhaps to a certain extent for oxygen also. Since water under all conditions is somewhat dissociated into H- and OH-ions, these are presented to the adsorbing root surfaces along with the molecules of water, although in infinitely lesser numbers. This situation is of great significance in its relationship to plant nutrition. Not only do H- and OH-ions penetrate the absorbing membranes of microorganisms and higher plants

[37] Ignatieff conceives a dynamic equilibrium between ferric (Fe^{+++}) and ferrous (Fe^{++}) iron in the soil, with the former dominating when good aeration prevails. Under waterlogged conditions, the relationship is reversed. The ferrous iron probably enters the colloidal complex more readily than the ferric iron and apparently is more soluble and available. Ignatieff, V., "Determination and Behavior of Ferrous Iron in Soils," *Soil Sci.*, 51: 249–263, 1941.

A somewhat similar oxidation-reduction cycle seems to hold in respect to manganese in which alternate dehydration and hydration apparently determine whether Mn^{++++} (MnO_2) or Mn^{++} (MnO) shall dominate in the soil solution. Fujimoto, C. K. and G. D. Sherman, "Behavior of Manganese in the Soil and the Manganese Cycle," *Soil Sci.*, 66: 131–145, 1948.

[38] Livingston, B. E. and Ruth Beal, "The Soil as a Direct Source of Carbon Dioxide," *Plant Physiol.*, 9: 237–259, 1934. The authors estimate that at times plants may obtain as much as 5 per cent of their carbon from the soil.

but they also determine the pH of the soil solution and plant sap. In practice, soil reaction is deemed of such importance that the pH is always one of the factors that should be considered in making a soil fertility decision.

2:11. SOIL AND PLANT INTERRELATIONS

It might hastily be assumed from what has been said regarding the transfer of nutrients that their solubility and availability are due entirely to a series of soil phenomena, the plant simply absorbing in a passive sort of way that which is presented. Such, however, is certainly not the case. The rootlets and root hairs are in most instances in very intimate contact with the soil colloidal surfaces. In fact, the relationship is so close that nutrients are thought by some authorities to pass from the soil solids to the plant without leaving the sphere of colloidal influence.[39] The nutrients thus appropriated are soluble but have not appeared in the soil solution as free, unadsorbed migrating ions or molecules. (See Fig. 2:6.) By intimate contact, plants may acquire nutrients before they have a chance to enter the soil solution proper and suffer loss by drainage.[40] An availability may thus be encouraged that otherwise might not take place so readily.

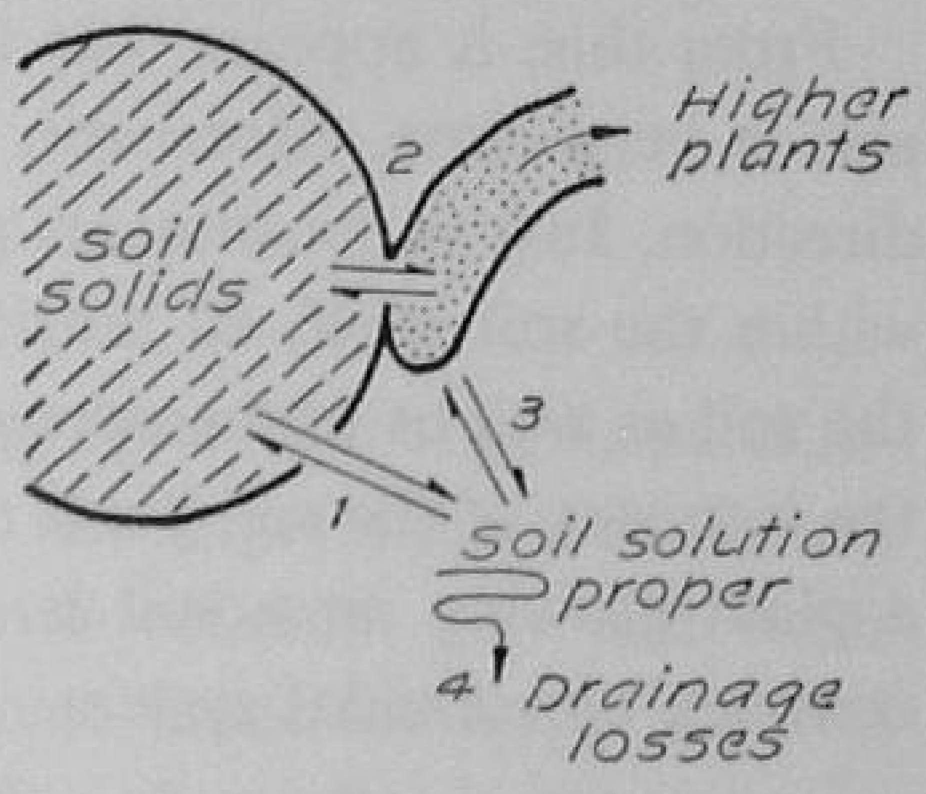

FIG. 2:6. *Diagram suggestive of the (1) interchange between the soil solids (colloidal and non-colloidal) and the soil solution proper, (2) movements of constituents to and from the plant root surfaces within the zone of colloidal influence (contact zone), and (3) interchange between the free soil solution and the absorbing surfaces of plant root systems. The loss of nutrients in drainage (4) is from the free portion of the soil solution.*

This contact effect apparently is much accentuated by root exudates and by microbial activity in the immediate neighborhood of the absorbing sur-

[39] See Jenny, H. and R. Overstreet, "Cation Interchange between Plant Roots and Soil Colloids," *Soil Sci.*, 47: 257–272, 1939; and Burd, John S., "Mechanism of Release of Ions from Soil Particles to Plants," *Soil Sci.*, 64: 223–225, 1947. Also see Williams, D. E., and N. T. Coleman, "Cation Exchange Properties of Plant Root Surfaces," *Plant and Soil*, 2: 243–256, 1950.

[40] This postulates two interdependent phases of soil solution: (1) that of the contact zones, rather small in volume and (2) that external thereto. The latter usually is much greater in amount and its solutes are much less influenced by the colloidal complexes. A nutrient present in the contact zones is soluble but does not function as freely as though present in the soil solution proper. It is not subject to loss in drainage unless dislodged in some way. Chapman, H. D., "Absorption of Iron from Finely Ground Magnetite by Citrus Seedlings," *Soil Sci.*, 48: 309–313, 1939.

faces. Plant roots not only give off large amounts of CO_2 but possibly other acid-forming substances as well. These, functioning at the soil-plant interfaces, no doubt speed up interchange to a remarkable degree. Also organic matter is continually being sloughed off by plant roots, thus providing food and energy for microorganisms. The concentration of microbial activity within the rhizosphere is ample proof of this.[41] Such biochemical phenomena cannot fail to increase greatly the rate and ease of transfer of nutrients from soil to plant.

From this, it appears that the relationship between plant roots and the soil is very close. Moreover, the flow of nutrients is not wholly in one direction. Just as constituents pass from a soluble to an insoluble condition within the soil itself, so nutrients are passing from plant roots back into the soil as well as in the opposite direction. These facts serve to emphasize the intricacy of the soil-plant relationship as well as to indicate clearly that a plant growing on a soil is an integral part, for the time being, of the complex biocolloidal system.

2:12. SOIL FERTILITY INFERENCES

Certain practical conclusions are inescapable in respect to the plant nutrient relationships just presented. An adequate supply of each nutrient must be maintained in the soil. In addition, provision must be made for a rate of availability suitable to normal crop growth. This involves a more or less complex transfer to the soil solution and to the plant, the latter seeming to participate in ways other than those of mere absorption.

Moreover, an adequate nutrient proportion is requisite, the total concentration of available nutrients being vital. Such a balance tends to insure the desirable physiological conditions necessary for successful plant production. The pH of the soil solution, since it influences profoundly many of the important soil and plant processes, plays a critical role in such an adjustment. Soil management, to be successful, must encompass all of these phases.

[41] Starkey, for instance, has demonstrated the localization of microorganisms around rootlets and root hairs. While bacteria seemed to dominate, fungi and actinomyces were also present in appreciable numbers. The organisms were by no means confined to dead roots but were very numerous on the surfaces of living ones as well, possibly because of excretions suitable as microbial food. Starkey, R. L., "Some Influence of the Development of Higher Plants upon the Micro-Organisms in the Soil, VI., Microscopic Examination of the Rhizosphere," *Soil Sci.*, 45: 207–227, 1938. See also, Clark, F. E., "Soil Microorganisms and Plant Roots," *Advances in Agronomy*, Vol 1: 242–282, (A. G. Norman, Ed.) Acad. Press Inc., 1949.

CHAPTER

3 Some Important Physical Properties of Mineral Soils

PHYSICALLY, a mineral soil is a porous aggregate of inorganic particles with an admixture of decaying organic matter. The larger mineral fragments usually are inbedded in and coated over with colloidal gels and other materials in a fine state of subdivision. In some cases the larger mineral particles predominate and a gravelly or a sandy soil results. In other cases, the mineral colloidal gels are in such amounts as to give the soil clayey characteristics. All gradations between these extremes are found in nature. The colloidal organic matter imparts physical and biochemical properties that have much to do with the capacity of soils to support higher plants and microorganisms.

The mineral particles of a soil range in size from those easily discernible with the naked eye (stone, gravel, and sand) to those within the range of the electron-microscope (ultra-clay). In discussing the size or sizes of these mineral particles, the term *texture* is commonly used. Thus, the texture of a particular soil may be coarse, medium, fine, or very fine depending on the group or groups of particles that dominate.

In the time covered by a generation of man, the soil processes, while surprisingly active, usually do not alter appreciably the size of the individual mineral particles. Thus a sandy soil remains sandy and a clay soil remains a clay. However, this does not prevent a change in the intensity of the physical properties of a soil. The addition of organic matter, for example, may have such an influence on the properties both of a sand and a clay as to alter profoundly their mechanical and nutrient relationships to higher plants. Again the downward movement of some of the clay particles from the surface layers into the subsoil often modifies the physical nature of both zones, thus affecting the rapidity of drainage and the degree of aeration.

3:1. CLASSIFICATION OF SOIL PARTICLES AND MECHANICAL ANALYSIS

In order to study successfully the mineral particles of a soil they are usually separated into convenient groups according to size. The various groups are spoken of as *separates*. While a classification based on size is arbitrary, it does make possible an actual separation and percentage evaluation. The analytical procedure by which the particles are thus separated is called a *mechanical analysis*. It is a determination of the particle size distribution.

As might be expected, a number of different classifications have been devised. Two of the most important will be cited, that established by the United States Department of Agriculture and that later advanced by the International Society of Soil Science.[1] They will be found in Tables 3:1 and 3:2 respectively with representative mechanical analyses.

Table 3:1. The Classification of Soil Particles as Established by the United States Department of Agriculture.[2] The Mechanical Analyses of Three Soils Are Also Given.

Separate	*Diameter Limits, mm.*	*Sandy Loam, Per Cent*	*Loam Soil, Per Cent*	*Clay Soil, Per Cent*
1. Very coarse sand[3]	2.00–1.00	3.1	4.3	0.2
2. Coarse sand	1.00–0.50	10.5	6.0	0.3
3. Medium sand	0.50–0.25	8.2	4.5	1.4
4. Fine sand	0.25–0.10	25.3	11.7	4.8
5. Very fine sand	0.10–0.05	22.0	13.2	16.8
6. Silt[4]	0.05–0.002	21.1	43.2	28.0
7. Clay	below 0.002	9.8	17.1	48.5

In the first column of each table are given the names of the various separates, and in the second the range in size of each group. Columns three,

[1] Shaw studied the two classifications, especially with regard to the use of their data in deciding the class names of soils. He finds it difficult to harmonize the significance of the figures. Shaw, C. F., "Field Textures and Physical Composition Determined by Two Methods of Mechanical Analysis," *Trans. Third Internat. Cong. Soil Sci.*, 1: 42–46, Oxford, Eng., 1935.

[2] Briggs, L. J., *et al.*, *The Centrifugal Method of Soil Analysis*, Bulletin 24, Bureau of Soils, U. S. Dept. of Agriculture, 1904.

[3] Originally this separate was spoken of as *fine gravel*. The present designation is more appropriate as it avoids confusion with the larger and more typical gravel particles.

[4] Previous to 1938 the silt range was set at .05–.005. This must be kept in mind in dealing with mechanical analyses made before that date.

Table 3:2. The Classification of Soil Particles as Established by the International Society of Soil Science.[5] The Mechanical Analyses of Three Soils Are Also Given.[6]

Separate	*Diameter Limits, mm.*	*Sandy Loam Shropshire, Per Cent*	*Loam Anglesey, Per Cent*	*Heavy Clay Czechoslovakia, Per Cent*
Coarse sand	2.00–0.20	66.6	27.1	0.9
Fine sand	0.20–0.02	17.8	30.3	7.1
Silt	0.02–0.002	5.6	20.2	21.4
Clay	below 0.002	8.5	19.3	65.8

four, and five show the percentages of each separate in three very different specimen soils, a sandy loam, a loam, and a clay. In order to obtain such figures, a sample of soil must actually be separated into the arbitrary groups. The percentage of each group in respect to the whole soil is then calculated from the dry weights obtained. This operation is the mechanical analysis already mentioned.[7]

Stone and gravel, while they figure in the practical examination and evaluation of a field soil, do not enter into the analysis of the fine earth. Their amounts are usually rated separately. The organic matter, ordinarily comparatively small in quantity, either is allowed to distribute itself through the various mineral groups or more often is removed by oxidation previous to the mechanical separation. The percentage of total organic matter, however, is generally quoted separately as it throws additional light on the probable physical nature of the soil in question. The percentage of calcium carbonate, if this salt is present, may also be given.

Sand, when dominant in a soil, gives properties known to everyone as

[5] Based on Atterberg, A., "Die Mechanische Bodenanalyse und die Klassifikation der Mineralboden Schwedens," *Internat. Mitt. für Bodenkunde*, 2: 312–342, 1912.

And Schucht, F., "Uber die Sitzung der Internationalen Kommission für die Mechanische und Physikalische Bodenundersuchung in Berlin am 31, October, 1913," *Internat. Mitt. für Bodenkunde*, 4: 1–31, 1914.

[6] Robinson, G. W., *Soils, Their Origin, Constitution, and Classification*, Thomas Murby and Co., London, 1936, p. 15.

[7] The principle involved in the method is simple. When soil particles are suspended in water, they tend to sink and the rapidity of settling is roughly proportional to their size. The suspension of a sample of soil is, therefore, the first step; the second step is that of settling and the withdrawal by some means of successive grades; and the third step is the determination of the percentage of each group of particles based on the original sample.

The apparatus and techniques are rather complicated. For an over-all and up-to-date discussion consult: Kilmer, V. J., and L. T. Alexander, "Methods of Making Mechanical Analyses of Soils," *Soil Sci.*, 68: 15–24, 1949.

sandy or *light*.[8] On the other hand, if the soil is made up largely of silt and clay, its plasticity and stickiness indicate that it is likely to be difficult to work or *heavy*. The characteristics of the soils of Tables 3:1 and 3:2 may be inferred readily from their mechanical analyses.

Not only is a mechanical analysis valuable in picturing in a general way the physical properties of a soil but it is also of use in deciding as to the textural name—that is, whether a soil is a sand, sandy loam, loam, etc. This phase is considered in section 3:5.

3:2. THE PHYSICAL NATURE OF THE SOIL SEPARATES

The coarse separates. Stone, gravel, and sand, because of their sizes, function as separate particles. The first two range in size from 2 mm. upward and may be more or less rounded, irregularly angular, or even flat as the case may be.[9] Sand grains also may be rounded or quite irregular, depending on the amount of abrasion that they have received. (See Fig. 3:1.) When not coated with clay and silt, such particles exhibit practically no plasticity and stickiness, and as a consequence, are little influenced by changes in moisture content. Their water-holding capacity is low, and because of the large size of the spaces between the separate particles, the passage of percolating water is rapid. They, therefore, facilitate drainage and encourage good air movement. Soils dominated by sand or gravel, therefore, are of open character, possess good drainage and aeration, and are usually in a loose friable condition.

FIG. 3:1. *Sand grains from soil. Note that the particles are irregular as to size and shape. While quartz usually predominates, other minerals may also occur. The particles are often iron stained or coated with humic material.*

[8] The terms "light" and "heavy" as commonly used in respect to soils refer to handling properties in the field and not to actual weights. Sandy soils work easily and hence are described as *light*. Clayey soils are more cohesive and therefore require greater power to plow and cultivate. Since they are less easily worked, they are referred to as *heavy*. Later it will be found, however, that under field conditions the dry weight of clayey soils when in good tilth is likely to be less than that of sandy or so-called light soils. See pages 58–59.

[9] The distinction between gravel and stone is now technically based on size. Gravel, chert, and slate are considered to range from 2 mm. up to 3 inches along

Clay and silt. The clay particles commonly are mica shaped and when moist are highly plastic. Therefore, when clay is wetted with a suitable amount of water, it expands and becomes sticky. On drying, it shrinks with the absorption of considerable energy. On wetting again, swelling occurs with the evolution of heat. This is called the *heat of wetting*. The adsorptive capacity of clays for water, gases, and soluble salts is very high. The diagram in Figure 3:2 shows how these properties increase as the particle size becomes smaller.

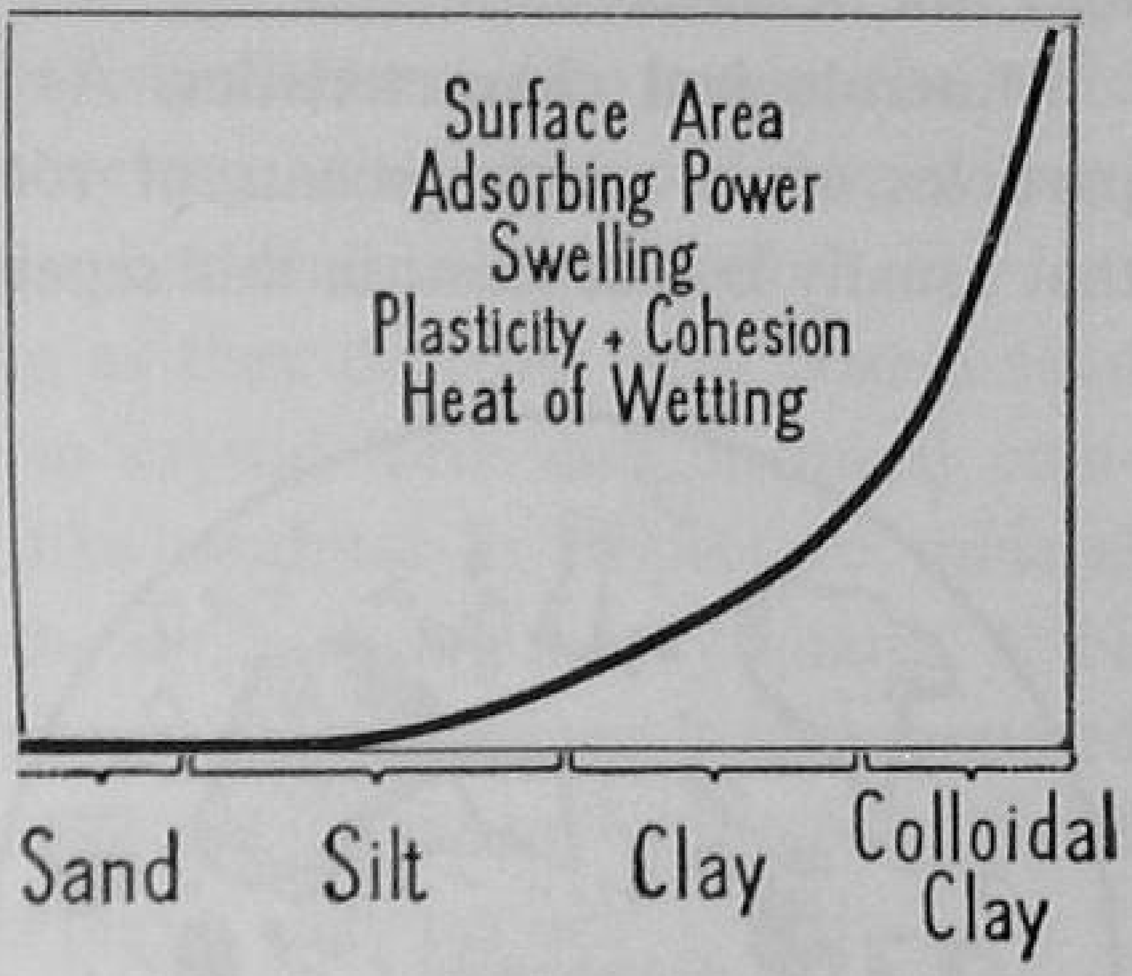

FIG. 3:2. *The finer the texture of a soil, the greater is the effective surface exposed by its particles. Note that adsorption, swelling, and the other physical properties cited follow the same trend and that their intensities go up rapidly as the colloidal size is approached. All this is of tremendous practical importance, not only physically but chemically as well.*

In contrast with the plate-like clay, silt particles are irregularly fragmental, diverse in shape, and seldom smooth or flat. (See Fig. 3:3.) In fact, they really are microsand particles, quartz being the dominant mineral. The silt separate possesses some plasticity, cohesion (stickiness), and adsorption due to an adhering film of clay but, of course, to a much lesser degree than the clay separate itself. In fact, the influence of silt is such as to make it a rather unsatisfactory soil constituent physically unless supplemented by adequate amounts of sand, clay and organic matter.

The presence of silt and especially clay in a soil imparts to it a fine texture, and a slow water and air movement. Such a soil is highly plastic, becoming sticky when too wet, and hard and cloddy when dry unless properly handled. The expansion and contraction on wetting and drying usually are great. And the water-holding capacity of clayey and silty soils generally is high. As already mentioned, such soils are spoken of as *heavy* because of their difficult working qualities, markedly in contrast with *light* easily tilled sandy and gravelly surface soils.

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their greatest diameter. Stone, cobbles, and boulders, on the other hand, exceed 3 inches in respect to their greatest dimension. Note that these differentiations are not in line with the popular concept that all gravels are rounded and smooth and that all stones are roughly irregular.

3:3. THE MINERALOGICAL AND CHEMICAL COMPOSITIONS OF SOIL SEPARATES

Although at this point our interest in soil particles is largely a physical one, a glance at their mineralogical make-up and chemical composition may not be amiss.

Minerological characteristics. As already suggested, the coarsest sand particles often are fragments of rock as well as of quartz, the mineral that usually is ascendant in this separate. Quartz also commonly dominates the finer grades of sand as well as the silt separate. (See Figs. 3:1 and 3:3.) In addition, variable quantities of other minerals usually occur such as the various feldspars and micas, magnetite, epidote, tourmaline, zircon, garnet, olivine, and rutile. However, some are so sparingly present as to be of little importance. Gibbsite, hematite and the limonite minerals also are found, the latter two imparting various shades of red and yellow if present in sufficient quantities. The soils of our Piedmont plateau and well oxidized tropical earths are good examples.[10]

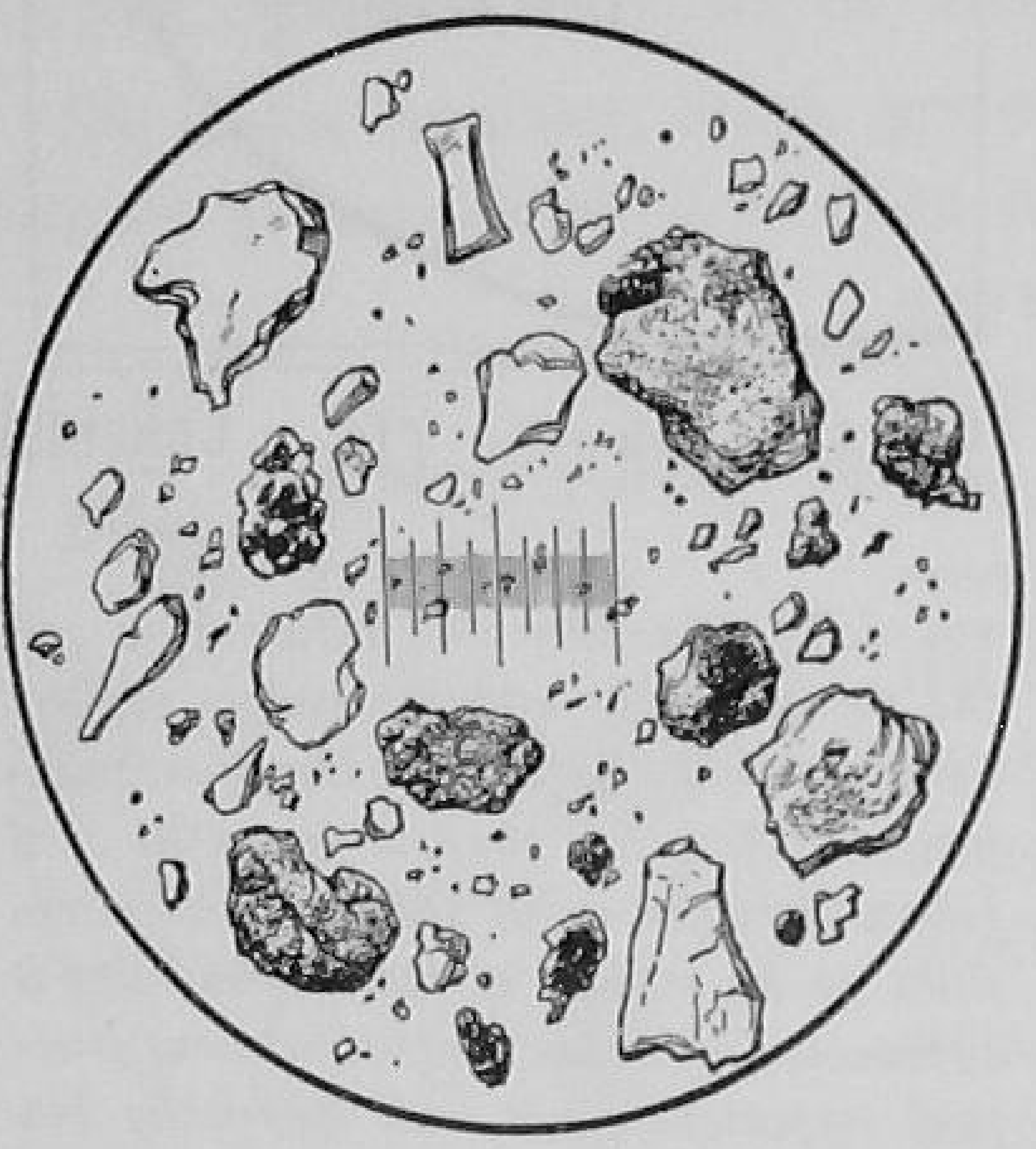

FIG. 3:3. *Very fine sand and silt particles as they appear under an ordinary microscope. Particles below ten spaces (see scale) in diameter are silt. Differences in the shapes of the various particles are striking. Quartz usually predominates both in sand and silt.*

Some of the clay particles, especially those in the coarser clay fractions, are composed of the minerals already cited as quartz, hematite, and gibbsite. An even more important group, however, is the complex alumino-silicates. Three such mineral types are at present recognized although future investigation undoubtedly will refine the classification—*kaolinite, illite,* and *montmorillonite*. It will suffice at this time to say that these groups vary markedly in plasticity, cohesion, and adsorption, the kaolinite being lowest in each case and the montmorillonite highest. It is, therefore, of considerable importance as to which clay type dominates or codominates any particular soil.

[10] For methods of making mineralogical analyses of soils, see: Jeffries, C. D., and M. L. Jackson, "Mineralogical Analysis of Soils," *Soil Sci.*, 68: 57–73, 1949.

Chemical make-up. Chemically kaolinite and the other members of that particular group are aluminum silicates. The same is true for montmorillonite and other clays of that same crystal pattern, but they also carry in addition sodium, iron, or magnesium as the case may be. Illite, often referred to as hydrous mica, is a potassium aluminum silicate. Its high potash content gives it a special nutrient significance. Obviously, the word clay, as now understood, is a term covering substances differing widely, not only mineralogically and chemically, but physically as well.[11]

If the various soil separates, ranging as they do from very coarse sand to ultra-fine clay, differ so markedly in crystal form and chemical composition, will they not also show a like contrast in respect to mineral nutrients? Logically we would expect the sands, being mostly quartz, to be lowest and the clay separate to be highest. This inference is substantiated by the data in Table 3:3. The general relationships shown by these data hold true for most soils, although some exceptions may occur.

Table 3:3. Composition of Separates from Various United States Surface Soils[12]

Separate	*Soils Developed from Indicated Materials*				
	Crystalline Residual	*Limestone Residual*	*Coastal Plain*	*Glacial & Loessial*	*Arid*
			PER CENT P_2O_5		
Sand	0.07	0.28	0.03	0.15	0.19
Silt	0.22	0.23	0.10	0.23	0.24
Clay	0.70	0.37	0.34	0.86	0.45
			PER CENT K_2O		
Sand	1.60	1.46	0.37	1.72	3.05
Silt	2.37	1.83	1.33	2.30	4.15
Clay	2.86	2.62	1.62	3.07	5.06
			PER CENT CaO		
Sand	0.50	12.26	0.07	1.28	4.09
Silt	0.82	10.96	0.19	1.30	9.22
Clay	0.94	9.92	0.55	2.69	8.03

3:4. SOIL CLASS—THE TEXTURAL NAMES OF SOILS

As soils are composed of particles varying greatly as to size and shape, specific terms are needed which will convey some idea of their textural

[11] See Chapter 4 for an extended consideration of the various types of clay and their properties.

[12] Failyer, G. H., and others, *The Mineral Composition of Soil Particles,* Bulletin 54, Bureau of Soils, U. S. Dept. of Agriculture, 1908.

Data in respect to the distribution of silicon, iron, aluminum, titanium, calcium, and magnesium through the various separates as reported by Joffe and Kunin are

make-up and give some indication of their physical properties. For this, *class* names are used, such as sand, sandy loam, silt loam, and the like.

These class names have originated through years of soil study and classification and gradually have been more or less standardized because of the necessity of definite distinctions. Three broad yet fundamental groups of soils are recognized: *sands, loams,* and *clays.* On the basis of these, additional class names have been devised.

Sands. The *sand* group includes all soils of which the sand separates make up 70 per cent or more of the material by weight. The properties of such soils are, therefore, characteristically sandy in contrast with the stickier and more clayey nature of the heavier groups of soil. Two specific classes are recognized—*sand* and *loamy sand.*

Clays. A soil to be designated as a *clay* must carry at least 35 per cent of the clay separate and in most cases not less than 40 per cent. So long as the percentage of clay is 40 or above, the characteristics of this separate are distinctly dominant and the class name is *sandy clay, silty clay,* or which is commonest of all simply *clay.* It is well to note that sandy clays often contain more sand than clay. Likewise, the silt content of silty clays usually exceeds that of the clay fraction itself.

Loams. The *loam* group, which contains many subdivisions, is more difficult to explain. In mechanical composition, it is more or less midway between sand and clay. An ideal loam may be defined as such a mixture of sand, silt, and clay particles as to exhibit light and heavy properties in about equal proportions. Roughly it is a half-and-half mixture on the basis of properties. However, the sum of the sands and the sum of the silt and clay generally are not, as one might guess, 50 per cent, respectively. The sands usually are definitely less than 50 per cent.

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given below. The soil fractionated was a Montalto silt loam of New Jersey, a residual product from basalt. The figures quoted are for the surface eight inch layer only.

Chemical Composition of Montalto Silt Loam Fractions [a]

Separate	SiO_2 %	Fe_2O_3 %	Al_2O_3 %	TiO_2 %	CaO %	MgO %
Sand	86.3	5.19	6.77	1.05	.37	1.02
Coarse silt	81.3	3.11	7.21	1.05	.41	.82
Fine silt	64.0	9.42	12.00	1.05	.32	2.22
Coarser clay	45.1	13.50	21.10	.96	.38	2.09
Finer clay	30.2	17.10	22.80	.88	.08	1.77

[a] Joffe, J. S., and R. Kunin, "Mechanical Separates and Their Fraction in the Soil Profile: I. Variability in Chemical Composition and Its Pedogenic and Agropedogenic Implications," *Proc. Soil Sci. Soc. Amer.*, 7: 187–193, 1942.

Because of the intermixture of coarse, medium, and fine particles, soils recognized simply as loams are, in most cases, of suitable physical character. Usually they possess the desirable qualities both of sand and clay without exhibiting those undesirable properties, such as extreme looseness and low water capacity on the one hand and stickiness, compactness, and slow air and water movement on the other.

Most soils of agricultural importance are some type of loam. They may possess the ideal make-up described above and be classed simply as *loam.* In most cases, however, the quantities of sand, silt or clay present are such as to require a modified class name. Thus, a loam in which sand is dominant is classified as a *sandy loam* of some kind; in the same way there may occur *silt loams, silty clay loams,* and *clay loams.*

Variations in the field. It readily can be seen that the textural names already established—*sand, loamy sand, sandy loam, loam, silt loam, silty clay loam, clay loam, sandy clay, silty clay,* and *clay*—form a more or less graduated sequence from soils that are coarse in texture and easy to handle to those, the heavy clays, that are very fine and difficult to manage. It is also obvious that these class names in a broad way are a reflection not only of particle-size distribution but also of tillage characteristics and other

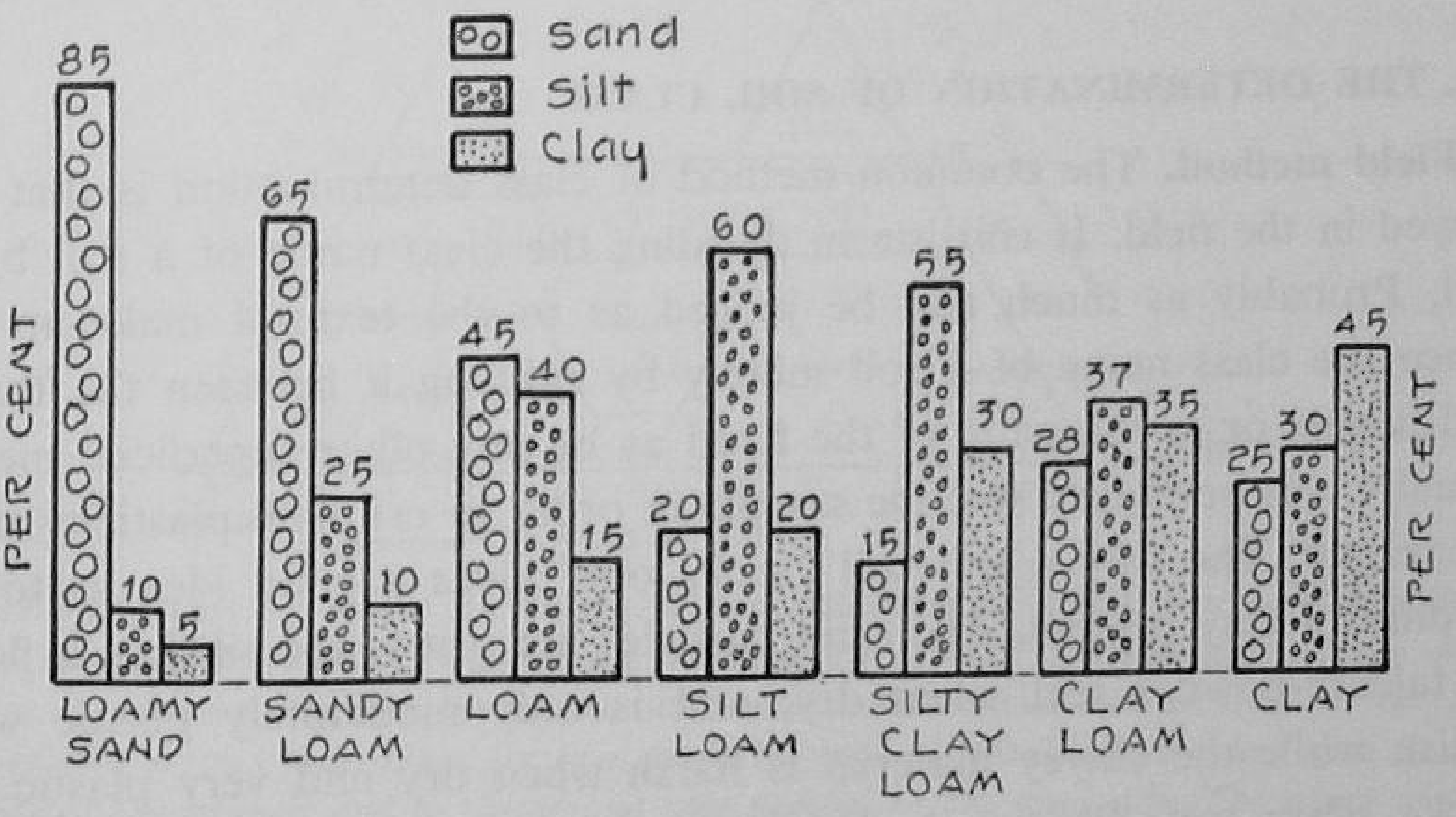

FIG. 3:4. *Graphic representation of the mechanical analyses of representative mineral soils.*

physical properties. Soil-minded persons should be fully familiar with the concept underlying the nomenclature employed. A study of Figure 3:4 will aid in its visualization.

Knowing as we do the complexity of normal soils, it is not surprising to find in the fields numerous variations from the ten classes already set up. This is because the several groups grade into each other in a most confusing way. Moreover, qualifying factors such as stone, gravel and the various grades of sand must be descriptively taken into consideration. Even silt and clay become qualifying terms in practice. All this will be obvious when the lists below are examined.

Sandy Soils	*Loam Soils*	*Clayey Soils*
Gravelly sands	Stony sandy loams	Stony clays
Coarse sands	Gravelly sandy loams	Gravelly clays
Medium sands	Coarse sandy loams	Sandy clays
Fine sands	Medium sandy loams	Silty clays
Very fine sands	Fine sandy loams	Clays
Loamy sands	Very fine sandy loams	
	Loams, gravelly loams, and stony loams	
	Silt loams and stony silt loams	
	Silty clay loams	
	Clay loams and stony clay loams	

3:5. THE DETERMINATION OF SOIL CLASS

Field method. The common method of class determination is that employed in the field. It consists in deciding the class name of a soil by its feel. Probably as much can be judged as to the textural make-up and hence the class name of a soil merely by rubbing it between the thumb and fingers or in the palm of the hand as by any other superficial means. Usually it is helpful to wet the sample in order to estimate plasticity more accurately. The way a wet soil "slicks out" gives a good idea as to the amount of clay present. The sand particles are gritty, the silt has a floury or talcum-powder feel when dry, and is only moderately plastic when moist, while the clayey material is harsh when dry and very plastic and sticky when wet. Persistent cloddiness generally is imparted by silt and especially by clay.

The method as outlined is used in all field operations, especially in soil survey, land classification, and the like. Accuracy in such a determination is of great practical value and depends largely on experience. Facility in

class determination is one of the first things a field man should develop, and it can only be acquired by the careful study and evaluation of known samples.

Laboratory method. A more accurate and fundamental method has been devised by the United States Department of Agriculture for the naming of soils based on a mechanical analysis. This method of identification is shown diagrammatically in Figure 3:5. The diagram reemphasizes that a soil is a mixture of different sizes of particles and that a close correlation exists between particle size distribution and the properties of soils. Obviously when mechanical analyses of the field soils that he has been working with are available to a surveyor, he can readily check on the accuracy of his class designations. A working knowledge of this method of naming soils is, of course, very essential. The legend explains the use of the triangular chart devised for this purpose.[13] (See Fig. 3:5.)

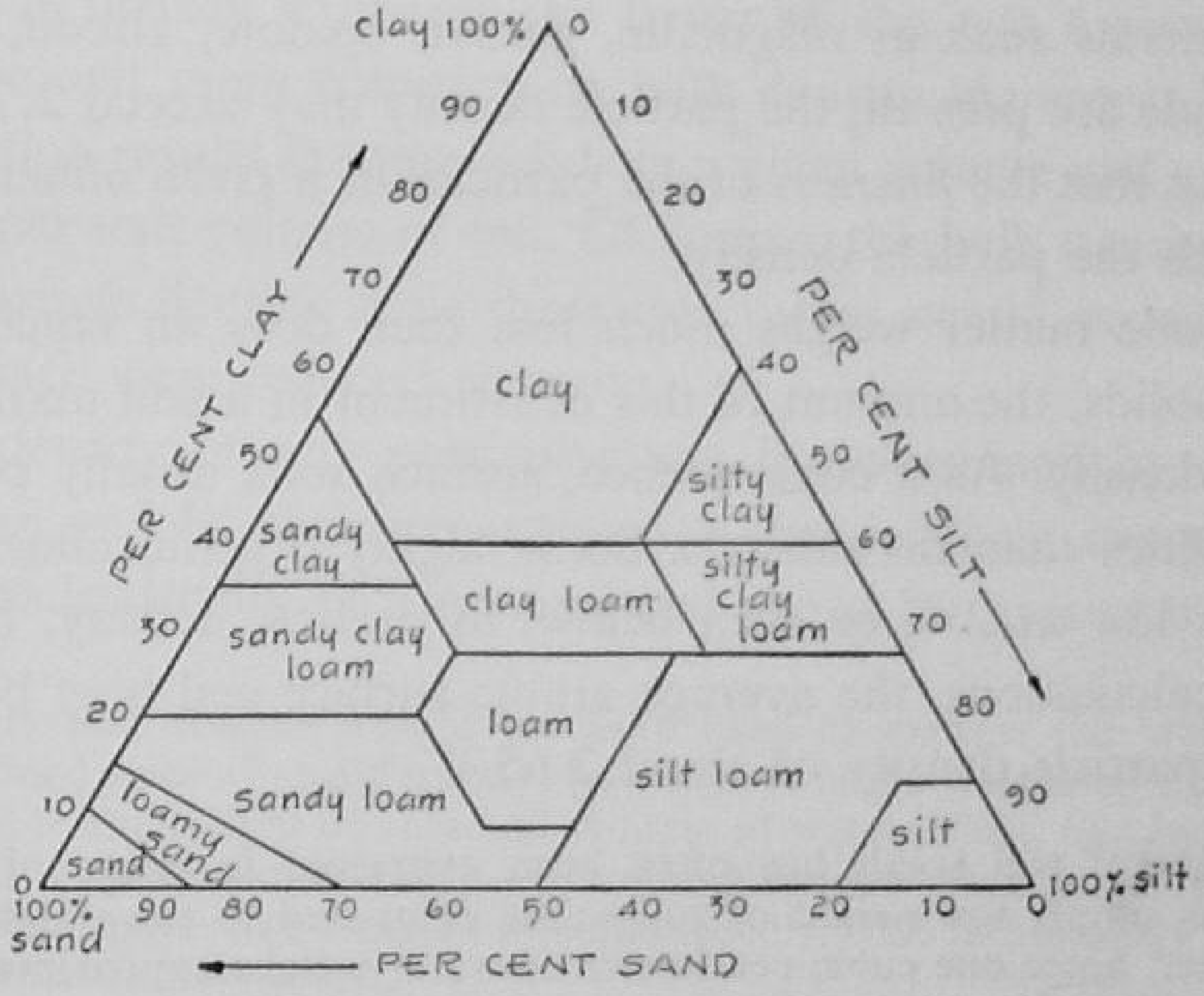

FIG. *3:5. Diagram by means of which the textural name of a soil may be determined from a mechanical analysis. In using the diagram, the points corresponding to the percentages of silt and clay present in the soil under consideration are located on the silt and clay lines respectively. Lines are then projected inward, parallel in the first case to the clay side of the triangle and in the second case parallel to the sand side. The name of the compartment in which the two lines intersect is the class name of the soil in question.*

[13] As a means of emphasizing still further the relationships between textural make-up and class names, apply the data appearing in Fig. 3:4 to the triangular chart. If your name designations check with those of the figure, your handling of the chart is correct.

3:6. THE PARTICLE DENSITY[14] OF MINERAL SOILS

One means of expressing soil weight is in terms of the density of the solid particles making up the soil. It is usually defined as the mass (or weight) of a unit volume of soil solids and is called the *particle density.* In the metric system particle density is usually expressed in terms of grams per cubic centimeter. Thus, if one cubic centimeter of soil solids weighs 2.6 grams, the particle density is 2.6 gms. per cc.

Particle density is unaffected by the arrangement of the soil solids, remaining the same whether the soil is loose or compact. Although considerable range may be observed in the density of the individual soil minerals, the figures for most mineral soils usually vary within the narrow limits of 2.60 and 2.75. This occurs because quartz, feldspar, and the colloidal silicates, with densities within this range, usually make up the major portion of mineral soils. Occasionally, however, when unusual amounts of heavy minerals such as magnetite, garnet, epidote, zircon, tourmaline, and hornblende are present, the particle density may exceed 2.75. It should be pointed out that the *fineness* of the particles of a given mineral has nothing to do with the particle density.

Since organic matter weighs much less than does an equal volume of the mineral solids, the amount of this constituent in a soil markedly affects the particle density. As a consequence, surface soils usually possess lower particle densities than do subsoils. Some highly organic mineral top soils may drop as low as 2.4, or even below, in particle density. Nevertheless, for general calculations, the average arable surface soil may be considered as having a particle density of about 2.65.[15]

[14] The weight of soil solids has often been expressed in terms of their *specific gravity.* This is simply the weight of soil solids compared to the weight of an equal volume of water. Since one cubic centimeter of water weighs approximately one gram there is little difference between *density* and specific gravity values. However, the latter has the disadvantage of being only a relative weight compared to that of water and consequently cannot be expressed in terms of units as is the case with density.

In keeping, therefore, with the accepted terminology of the Soil Science Society of America the expression *density* will be used in this text instead of specific gravity. But because of the insignificant differences in actual density and specific gravity values, specific gravity data will be used in most cases interchangeably with density data. See *Proc. Soil Sci. Soc. Amer.,* 13: 573, 1948.

[15] For methods of density determination and for data in respect to certain representative American soils see: Smith, W. O., "Density of Soil Solids and Their Genetic Relations," *Soil Sci.,* 56: 263–272, 1943.

3:7. THE BULK DENSITY (VOLUME WEIGHT)[16] OF MINERAL SOILS

Bulk density. This is a second and different method of expressing soil weight. In this case the *total soil space* (space occupied by solids and pore spaces combined) is taken into consideration. Bulk density[17] is defined as the mass (weight) of a unit volume of dry soil.[18] This volume would, of course, include both solids and pores. The comparative calculations of bulk density and particle density are shown diagrammatically in Figure 3:6. A careful study of this figure should make clear the distinction between these two methods of expressing soil weight.

Bulk density vs. particle density. Bulk density is a weight measurement by which the entire soil volume is taken into consideration. Particle density, in contrast, is concerned only with the solid particles. Since a given volume of soil solids weighs more than the same volume of soil (including pores), particle density is always the larger of the two figures. As a soil becomes more and more compact, its bulk density increases. This is true since compaction results in more solids in a given volume and consequently more weight per unit volume of soil. Of course, the bulk density can never exceed the particle density since these two values would become identical if the pore space were reduced to zero.

The bulk density of any particular soil is determined by the density of the particles and by their arrangement—that is, their *structural* condition. The particle density of a mineral soil shows no great variation from

[16] Bulk density and volume weight are both used to express the weight of soils. The latter is defined somewhat differently, however. It is the weight of a given volume of soil compared to the weight of an equal volume of water. Thus, like specific gravity, it is a comparative figure. Bulk density and volume weight values are almost identical and for practical purposes can be used interchangeably. The terminology *bulk density* will be used in this text, however.

[17] In the field the bulk density of a soil may be estimated by driving a cylinder of known volume into the ground and obtaining thereby a core of natural soil. By weighing the soil and then determining the amount of water that it contains, the amount of absolutely dry soil may be ascertained. Dividing this by the volume of the cylinder gives the figure for bulk density. For cylinders suitable for this mode of determination see: Coile, T. S., "Soil Samplers," *Soil Sci.*, 42: 139–142, 1936; and Yoder, R. E., "A Direct Method of Aggregate Analysis of Soils and a Study of the Physical Nature of Erosion Losses," *Jour. Amer. Soc. Agron.*, 28: 337–351, 1936. Also see: Dortignac, E. J., "A Simple Volume-Weight-Sampler and Procedure," *Soil Sci.*, 69: 95–105, 1950; and Jamison, V. C., H. A. Weaver, and I. F. Reid, "A Hammer-Driven Soil-Core Sampler," *Soil Sci.*, 69: 487–498, 1950.

[18] In order to have a constant and comparable basis for calculation, almost all soil data are computed on dry soil. Consequently, unless something is said to the contrary this should always be assumed.

time to time unless there is a marked change in organic content. Soil structure, therefore, becomes the major factor in accounting for normal fluctuations in bulk density.

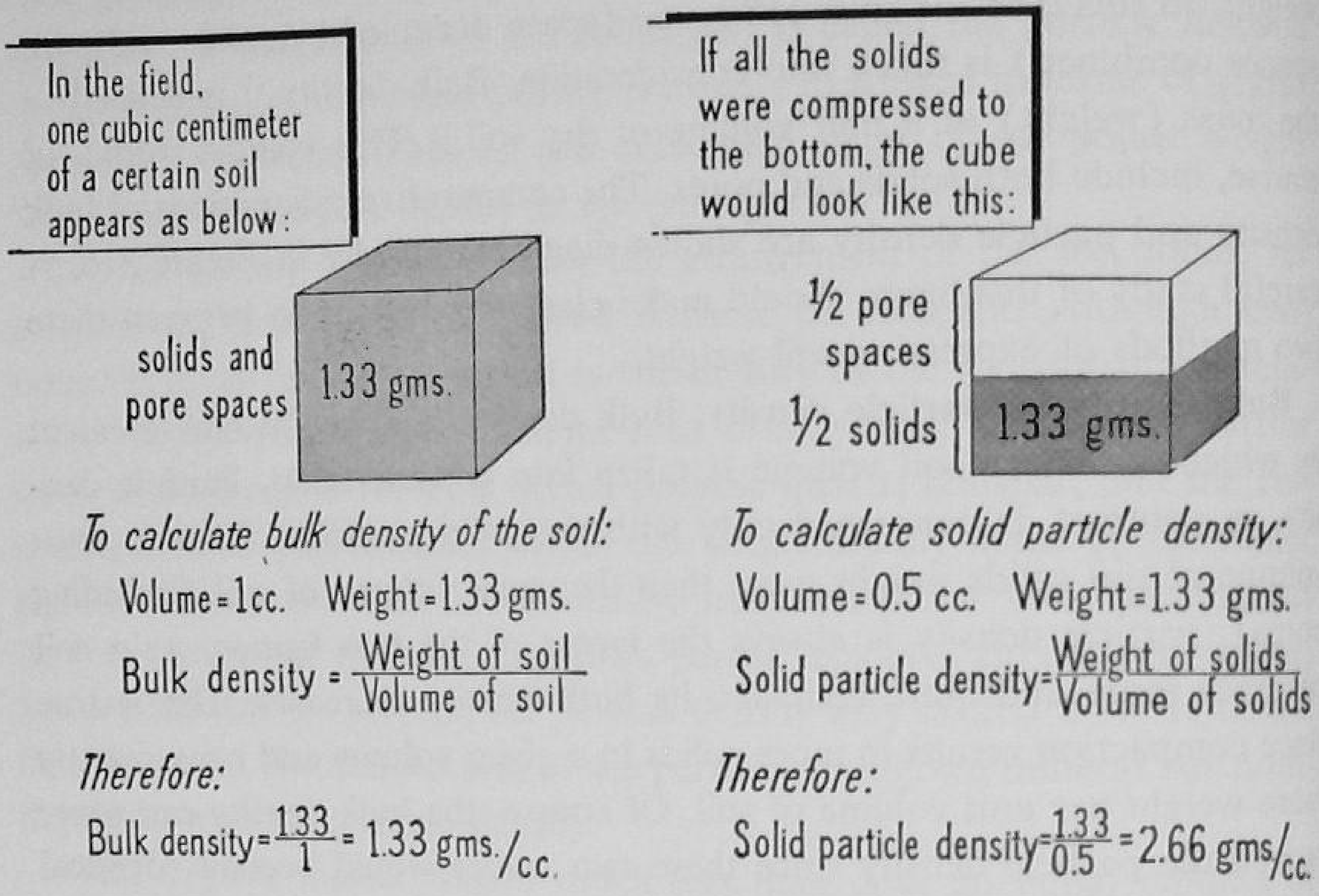

FIG. 3:6. *A diagrammatic representation of bulk density and particle density of soil. Follow the calculations through carefully and the terminology should be clear. In this particular case the bulk density is one half that of the particle density and the percentage pore space is 50.*

Factors affecting bulk density. Perhaps as much as any other single factor, soil structure determines the bulk density of a given soil. The particles of sandy soils generally tend to lie in close contact. Thus, with such soils the weight of a given volume is rather high. The low organic matter content of sandy soils further encourages this. The particles of the finer surface soils, such as silt loams, clay loams, and clays, on the other hand, ordinarily do not rest so close together. This is due to the fact that these surface soils are comparatively well granulated, a condition encouraged by their relatively high organic matter contents. Granulation encourages a fluffy, porous condition which results in low bulk density values. Consequently, the bulk density of a well granulated silt loam surface soil is sure to be lower than that of a representative sandy loam.

The bulk densities of clay, clay loam, and silt loam surface soils normally may range from 1.00 to as high as 1.60 grams per cc depending on their

condition. A variation from 1.20 to 1.80 may be found in sands and sandy loams. Very compact subsoils regardless of texture may have bulk densities as high as 2.0 grams per cc or even greater.

Even in soils of the same texture great differences in bulk density are to be expected when similar horizon levels are compared. This is clearly shown by data in Table 3:4 respecting Wisconsin silt and clay loams. Moreover, there is a distinct tendency for the bulk density to rise as the profile is penetrated. This apparently is due to a lower content of organic matter, less aggregation and root penetration and a compaction due to the weight of the overlying layers. Perhaps in certain cases a downward movement of clay, and iron and aluminum oxides, may give rise to especially dense layers.

Table 3:4. Bulk Density Data for Certain Wisconsin Profiles[19]

Horizon	*Marathon Silt Loam*	*Miami Silt Loam*	*Spencer Silt Loam*	*Superior Clay Loam*
Plow layer	1.34	1.28	1.38	1.46
Upper subsoil	1.49	1.41	1.55	—
Lower subsoil	1.59	1.43	1.66	1.66
Parent material	1.72	1.49	1.63	—

The system of crop and soil management employed on a given soil are likely to influence its bulk density especially of the surface layers. The addition of farm manure in large amounts tends to lower the weight figure of surface soils as does also a bluegrass sod. Intensive cultivation, on the other hand, operates in the opposite direction.

Data presented in Table 3:5 show this relationship very well. These data are from long-time experiments in four different states, the soils having been under cultivation for from 40 to 150 years. Not only did cropping increase the bulk density of the topsoils, but additional data from the Ohio experiment show that the second and third feet were also made more compact by cropping.

Other weight figures. When the bulk density of a soil is known in terms of grams per cc, its dry weight in pounds to the cubic foot may be found approximately by multiplying by 62.42 the standard weight of a cubic

[19] Nelson, L. B., and R. J. Muckenhirn, "Field Percolation Rates of Four Wisconsin Soils Having Different Drainage Characteristics," *Jour. Amer. Soc. Agron.*, 33: 1028–1036, 1941. See also: Harland, M. B., and R. S. Smith, "Volume Weight of Certain Field Soils," *Jour. Amer. Soc. Agron.*, 20: 533–541, 1928.

Table 3:5. The Influence of Cropping on the Bulk Densities of Certain Topsoils under Cultivation for from 40 to 150 years

Soil Type[20]	*Cropped Soil*		*Uncropped Soil*
	Years Cropped	*Bulk Density*	*Bulk Density*
Hagerstown loam (Penn.)	58	1.25	1.07
Marshall silt loam (Iowa)	50+	1.13	0.93
Nappanee silt loam (Ohio)	40	1.31	1.05
Ave. 19 Georgia soils	45–150	1.45	1.14

foot of water. Clayey and silty surface soils may vary from 65 to 100 pounds to the cubic foot, while sands and sandy loams may show a variation of 75 to 110 pounds. The greater the organic content, the less is this weight. Very compact subsoils, regardless of texture, may weigh as much as 125 pounds per cubic foot. The figures quoted are for the absolutely dry soil and do not include the water present.

The actual weight of a soil also may be expressed in terms of an acre-foot, referring to a volume of soil one acre in extent and one foot deep. The weight of an acre-foot of surface mineral soil commonly ranges from 3,000,000 to 4,500,000 pounds of dry substance. The figure most commonly used, however, is 2,000,000 or sometimes 2,500,000 pounds as the weight of average surface soil to a depth of 6 or 7 inches. This is considered as an *acre-furrow-slice*.

Bulk density, besides being an interesting and significant physical characteristic, is very important as a basis for certain computations. Weight figures, especially those for the furrow-slice, may be used to express the amounts of water, organic matter, and mineral constituents, either total or available, that are present. Moreover, bulk density is necessary in the calculation of the total pore space present in soil. The latter information affords a valuable means of judging and comparing soils.

[20] The above data were obtained, in order of their listing, from the following publications:

Alderfer, R. B., and F. G. Merkle, "The Measurement of Structural Stability and Permeability and the Influence of Soil Treatments upon These Properties," *Soil Sci.*, 51: 201–212, 1941.

Swanson, C. L. W., and J. B. Peterson, "The Use of the Micrometric and Other Methods for the Evaluation of Soil Structure," *Soil Sci.*, 53: 173–185, 1942.

Page, J. B., and C. J. Willard, "Cropping Systems and Soil Properties," *Proc. Soil Soc. Amer.*, 11: 81–88, 1946.

Giddens, Joel, and W. H. Garman, "Some Effects of Cultivation on the Piedmont Soils of Georgia," *Proc. Soil Sci. Soc. Amer.*, 6: 439–446, 1941.

3:8. THE PORE SPACE OF MINERAL SOILS

The pore space of a soil is that portion occupied by air and water. The amount of this pore space is determined largely by structural conditions—that is, by the interrelated influence of texture, compaction, and aggregation.

As already emphasized, the bulk density of coarse surface soils low in humus is high due to the close contact of the particles. Finer soils are generally lighter due to the readiness with which granulation occurs, especially when sufficient decomposing organic matter is present. This means that surface sands and sandy loams in general usually contain somewhat less pore space than silt loam, clay loam, and clay surface soils.

The validity of the above generalizations may readily be substantiated by the use of a very simple formula [21] involving particle density and bulk density figures. A sandy soil having a bulk density of 1.50 and a particle density of 2.65 will be found to have, when these figures are properly applied to the formula below, 43.4 per cent of pore space. A silt loam in which the corresponding values are 1.30 and 2.65 respectively, possesses 50.9 per cent of air and water space. This latter value is close to the pore capacity of a normally granulated silt loam or clay loam surface soil.

Factors influencing total pore space. As might be expected, considerable difference in the total pore space of various soils occurs depending upon conditions. Sandy surface soils show a range of from 35 to 50 per cent while heavy soils vary from 40 to 60 per cent or perhaps even more in cases of high organic matter and marked granulation. Pore space also varies with depth, some compact subsoils dropping as low as 25 or 30 per cent. This accounts in part for the inadequate aeration of such horizons.

The handling of a soil exerts a marked influence upon the pore space of the furrow-slice. For instance, the continuous bluegrass sod of the

[21] The derivation of the formula used to calculate the percentage of total pore space in soil is as follows:

$$\% \text{ solid space} = \frac{\text{Bulk density}}{\text{Particle density}} \times 100$$

Since,

$$\% \text{ pore space} + \% \text{ solid space} = 100$$

then

$$\% \text{ pore space} = 100 - \% \text{ solid space}$$

and

$$\% \text{ pore space} = 100 - \left(\frac{\text{Bulk density}}{\text{Particle density}}\right) \times 100$$

Hagerstown loam of Pennsylvania cited in Table 3:5 (page 60) had a total porosity of 57.2 per cent while the comparable rotation plot showed only 50 per cent. (See Table 3:6.) Additional data presented in this table from three other states show that cropping tends to lower the total pore space below that of the virgin or uncropped soils. This reduction usually is associated with a decrease in organic matter content and a consequent lowering of granulation. Pore space in the subsoil has been found to decrease with cropping, although to a somewhat lesser degree.

Size of pores. Two types of individual pore spaces in general occur in soils—*macro* and *micro*. While no sharp line of demarcation occurs, the macro pores characteristically allow the ready movement of air and percolating water. In contrast, in the micro type of pore, air movement is greatly impeded while water movement is restricted largely to slow capillary adjustment. Thus in a sandy soil, in spite of the low total porosity, the movement of air and water is surprisingly rapid due to the dominance of the macro spaces.

Table 3:6. The Influence of Cropping on the Per Cent Pore Space of Surface Soils from Four Different Areas [22]

Soil Type	*Cropped Soil*		*Uncropped Soil*
	Years Cropped	*% Pore Space*	*% Pore Space*
Hagerstown loam (Penn.)	58	50.0	57.2
Marshall silt loam (Iowa)	50+	56.2	62.7
Nappanee silt loam (Ohio)	40	50.5	60.3
Ave. 19 Georgia soils	45–150	45.1	57.1

Heavy soils allow only slow gas and water adjustment in spite of the unusually large amount of total pore space. Here the dominating micro pores often maintain themselves full of water. Aeration, especially in the subsoil, frequently is inadequate for satisfactory root development and desirable microbial activity. Thus the size of the individual pore spaces rather than their combined volume is the important consideration. The loosening and granulating of heavy soils promotes aeration, not so much by increasing the pore space in total but by raising the proportion of the macro spaces.

It has already been suggested (page 10 and Fig. 1:4) that in the case of a well granulated silt loam surface soil at optimum moisture for plant

[22] For references see footnote of Table 3:5.

growth, the total pore space not only may be near 50 per cent but also it is likely to be shared fairly equally by air and water. In such a case the micro pore space is not completely filled with water. Soil aeration under such a condition is likely to be fairly satisfactory especially if a similar ratio of air to water extends well into the subsoil.[23]

Cropping and size of pores. Continuous cropping, particularly of soils originally very high in organic matter, often results in a reduction of large or macro pore spaces. Data from a Rendzina soil in Texas presented in Table 3:7 show this effect very strikingly.

The amount of macro pore space, so necessary for ready air movement, was reduced about one-half by cropping the soil. This severe reduction in pore size extended into the 6 to 12 inch layer also. In fact, samples taken as deep as 42 inches showed the same trend.

A further examination of Table 3:7 shows that cultivation and cropping have appreciably reduced the total pore space. This was accompanied by

Table 3:7. The Effect of Continuous Cropping for at Least 40–50 Years on the Total Pore Space and the Macro- and Micro-pore Spaces in a Houston Black Clay from Texas[24]

Sampling Depth Inches	*Soil Treatment*	*Organic Matter (%)*	*Pore Space*		
			Total (%)	*Macro (%)*	*Micro (%)*
0–6	Virgin	5.6	58.3	32.7	25.6
	Cultivated	2.9	50.2	16.0	34.2
6–12	Virgin	4.2	56.1	27.0	29.1
	Cultivated	2.8	50.7	14.7	36.0

[23] Data presented by Wilson *et al*[a] in respect to an Ida silt loam profile of Iowa exemplify very well the ideal case presented above. The percentage figures are all on the volume basis.

Depth (Inches)	*Pore Space %*	*Water Space*[b] *%*	*Air Space %*
2– 6	51.0	28.6	22.4
6–12	51.7	27.4	24.3
12–18	51.0	28.7	22.3
18–24	51.2	28.6	21.6
24–30	50.6	29.8	20.8

[a] Wilson, H. A., F. F. Riechen, and G. M. Browning, "Soil Profile Characteristics in Relation to Drainage and Level Terraces," *Proc. Soil Sci. Soc. Amer.*, 11: 110–118, 1946.

[b] This percentage of water is the amount, approximately, that the soil will hold against gravity and probably is somewhat above optimum for crop growth. Air space is, therefore, somewhat depressed.

[24] Laws, W. D., and Evans, D. D., "The Effects of Long-time Cultivation on Some Physical and Chemical Properties of Two Rendzina Soils," *Proc. Soil Sci. Soc. Amer.*, 14: 15–19, 1949.

a more or less proportional rise in the space given over to micro pores. As would be expected, the decrease in pore size was associated with a corresponding decrease in organic matter content.

3:9. THE STRUCTURE OF MINERAL SOILS[25]

While *texture* undoubtedly is of great importance in determining certain characteristics of a soil, it is evident that the particular type of particle-grouping that happens to predominate must exert considerable influence also. The term *structure* is used to refer to such groupings. Structure is strictly a field term descriptive of the gross, over-all aggregation or arrangement of the soil solids. It is thus in distinct contrast with texture and is largely macroscopic in range.

A profile may be dominated by a single structural pattern. More often, however, a number of types of aggregation are encountered as progress is made from horizon to horizon. It is at once apparent that soil conditions and characteristics—such, for example, as water movement, heat transfer, aeration, bulk density, and porosity—will be much influenced by structure. In fact, the important physical changes imposed by the farmer in plowing, cultivating, draining, liming, and manuring his land are structural rather than textural.

Structural forms under virgin conditions apparently have been developed from one or both of two possible non-structural states—(1) *single grained* and (2) *massive*. In the former, the single, solid particles function as individuals. Loose sand is a good example of this. The binding influence of organic matter often modifies this original form to a certain extent by building up a weak aggregation.

In the massive non-structural case, the soil units originally are very large, irregular, and featureless as far as characteristic soil aggregates are concerned. However, as a soil is synthesized and a profile is developed, cleavages and disruptions occur and definite structural patterns begin to characterize the hitherto featureless mass.

Types of soil structure. These two extremes cited above are the theoretical boundaries of the seven structural types commonly recognized in soil profiles. They are as follows: *platy, columnar, prismatic, blocky, nut-*

[25] For a consideration of all phases of soil structure, see Baver, L. D., *Soil Physics,* John Wiley and Sons, Inc., New York, 1948, Chap. 5. Also consult: Russell, E. W., *Soil Structure,* Imp. Bur. Soil Sci., Tech. Commun., 39: 1938.

like, granular and *crumb*.[26] A brief description of each of these structural types with schematic drawings will be found in Figure 3:7. A more detailed description of each follows:

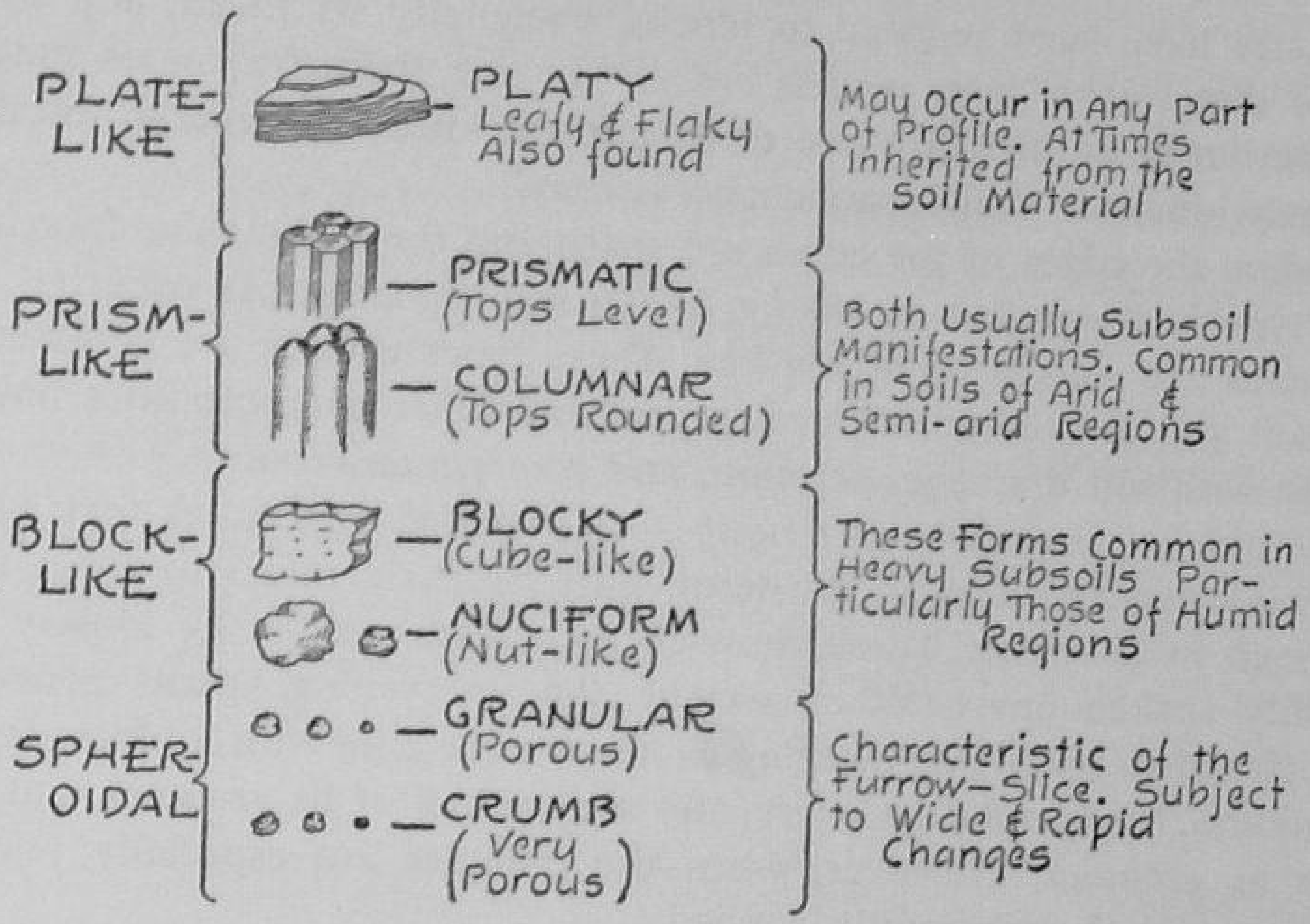

FIG. 3:7. *Diagrammatic representation of the various structural types found in mineral soils. Their location in the profile is suggested. In arable soils granulation usually receives the most attention.*

1. Plate-like—*Platy*—In this structural type the aggregates or groups are arranged in relatively thin horizontal plates, leaflets, or lenses. While most noticeable in the surface layers of virgin soils, such a pattern may characterize the subsoil horizons as well.

   Although most structural features are usually a product of soil forming forces, the *platy* type is often inherited from the parent materials, especially when the latter have been laid down by water or ice.
2. Prism-like—*Columnar* and *Prismatic*—These types are characterized by vertically oriented aggregates or pillars. These elongated columns vary in length with different soils and may reach a diameter of 6 inches or more. They commonly occur in the subsoil horizons of arid and semi-arid region soils and when well developed are a very striking feature of the profile.

   When the tops are rounded, the term *columnar* is used. This may occur when the profile is changing and certain horizons are degrading. When the tops of the prisms are still plane, level and clean cut, the structural pattern

[26] For a more complete consideration of classification see: Nikiforoff, C. C., "Morphological Classification of Soil Structure," *Soil Sci.*, 52: 193–207, 1941. And Report of Committee on Soil Structure, *Proc. Soil Sci. Soc. Amer.*, 10: 479–480, 1948.

is designated as *prismatic*. Both the prismatic and columnar types of aggregation are divided into classes depending on the size or horizontal diameter of the prisms.

3. Block-like—*Blocky* and *Nut-like* (nuciform)—In this case the original aggregates have been reduced to blocks, irregularly six faced, and with their three dimensions more or less equal. In size these fragments range from a fraction of an inch to three or four in thickness. In general, the design is so individualistic that identification is easy.

   When the edges of the cubes are sharp and the rectangular faces distinct, the type is designated as *blocky*. When sub-rounding has occurred, the aggregates are spoken of as *nut-like*. These types usually are confined to the subsoil and their stage of development and other characteristics have much to do with soil drainage, aeration, and root penetration.

4. Spheroidal—*Granular* and *Crumb*—All rounded aggregates may be placed in this category although the term more properly refers to those not over ½ inch in diameter. These rounded complexes usually lie loosely and are readily shaken apart. When wetted, the intervening spaces generally are not closed so readily by swelling as may be the case with a blocky structural condition. Ordinarily the aggregates are spoken of as granules and the pattern as *granular*. However, when the granules are especially porous, the term *crumb* is significantly applied.

   Granular and less frequently crumb structures are characteristic of many surface soils, especially those high in organic matter. They are the only types of aggregation that are most commonly influenced artificially, that is by practical methods of soil management.

   The maintenance of adequate granulation is, of course, a vital necessity especially with heavy surface soils. Much will be said later in respect to the degree of aggregation of surface soils, its stability, and its practical importance.

As already emphasized, two or more of the structural conditions listed usually occur in the same soil solum. In fact, all of the four main types might be found in one virgin profile, although this would be rather unusual. In humid temperate regions, a granular aggregation in the surface horizon with a blocky, nuciform or platy type of some kind in the subsoil is usual, although granular sub-horizons are not uncommon. In soils of arid regions the blocky or nut-like type in the subsoil may be replaced by a prismatic arrangement.

Genesis of soil structure. The mechanics of structure formation are exceedingly complicated and, as yet, rather obscure. Without a doubt the nature of the parent material and its origin are important factors. Also of some import are the physical and biochemical processes of soil formation, particularly those that result in the synthesis of clay and humus. Climate is,

therefore, a prime consideration. Soluble salts probably play an important role, particularly in the soils of arid regions. Nor should the downward migration of clay, of iron oxides, and of lime be overlooked. Undoubtedly, however, the accumulation of organic matter and its type of decay play a major role, especially in the development of the granular structure so common in the surface soils of grasslands. In fact, the preservation and encouragement of this particular structural type, since it occurs at the surface, become one of the most important soil problems of cultivated lands. Let us turn to this phase without further delay.

3:10. GRANULATION AND ITS PROMOTION IN ARABLE SOILS [27]

A soil granule is a rounded porous mass of mineral particles of varying sizes, usually irregularly interspersed with humus. Apparently its content of clay and humus is higher than that of the whole soil and its porosity is closely related to its organic content. Obviously, the ease with which air and water penetrate the individual granule is of great importance. Moreover, the magnitude of internal surfaces is of tremendous significance in respect to the adsorptive capacity of the soil and other reactive powers. In fact, most of the chemical and biochemical changes that occur in granular soils probably take place within the tortuous and endless mazes of their aggregates.

In well-granulated surface soils, 70 or 80 per cent or even more of the total mass may exhibit aggregation, although 40 or 50 per cent is more usual. However, sandy soils low in organic matter or heavy soils badly puddled, may possess a granulation as low as 20 or 30 per cent. Unless a soil is quite sandy such a low degree of aggregation forecasts a physical condition very unsatisfactory for crop growth. (See Fig. 3:8.)

Genesis of granules. Just what draws and holds the individual granule together, once the proper contacts have been made and the aggregate is

[27] Below will be found a few of the important articles available on soil aggregation, especially granulation:

Garey, C. L., and J. R. McHenry, "Dependence of Certain Physical and Chemical Measurements in a Soil Profile on the Type of Water Soluble Aggregates," *Proc. Soil Sci. Soc. Amer.*, 12: 44–49, 1947.

Olmsted, L. B., "Effect of Long Time Cropping Systems and Tillage Practices upon Soil Aggregation at Hays, Kansas," *Proc. Soil Sci. Soc. Amer.*, 11: 89–92, 1946.

Alderfer, R. B., and F. G. Merkle, "The Comparative Physical Constitution of Water Stable Granules and of the Original Soil," *Soil Sci.*, 53: 105–113, 1942.

Russell, E. J., and E. W. Russell, *Soil Conditions and Plant Growth*, Longmans, Green and Company, New York, 1950, Chap. 23.

assembled, is obscure, and hence is subject to considerable speculation.[28] In general terms, however, it can be said that granules probably develop from two initial sources—(1) by accretion or build-up from smaller units and (2) by the disintegration of larger and less stable aggregates. In cultivated soils, the former origin probably is the more common. Consequently, it will receive the most attention.

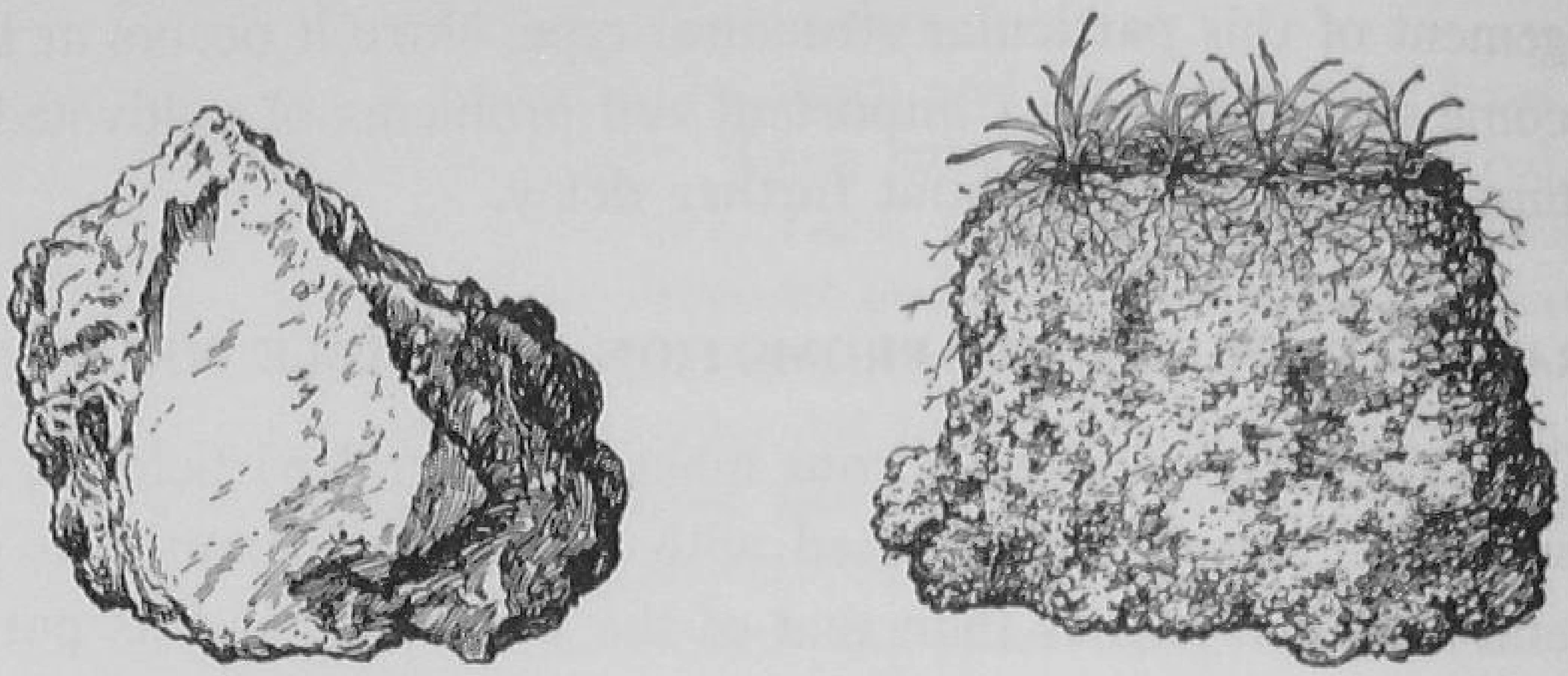

FIG. 3:8. *A puddled soil (left) and a well-granulated soil (right). Plant roots and especially humus play the major role in soil granulation. For that reason a sod tends to restore the structural condition of cultivated land.*

Several specific interrelated factors seem to account for granule genesis. Of these (1) wetting and drying, (2) freezing and thawing, (3) the physical activity of roots and soil animals, (4) the influence of decaying organic matter and of the slimes from the microorganisms and other forms of life, and (5) the modifying effects of adsorbed bases are most important. These factors in ever-changing intensity and coordination apparently encourage granule genesis to such an extent as to make the maintenance of a suitable physical condition possible even in intensively cultivated lands.

Obviously any action that will develop lines of weakness, shift the particles to and fro, and force contacts that otherwise might not occur, should encourage granulation. Consequently, it is not surprising that the alternate contraction and expansion of water films, the influences of freezing and thawing, the physical effects of root extension, and the mixing action of soil fauna tend to encourage a build-up. The benefits of fall plowing on certain types of soil and the slaking of clods under the influence of a gentle rain have long been known and taken advantage of in seedbed preparation. And the granulating influences of earthworms and other soil organisms should not be passed unnoticed.[29]

[28] A review of the theories concerning granulation will be found in Baver, L. D., *Soil Physics,* John Wiley and Sons, Inc., New York, 1948, pp. 135–151.

[29] For a discussion of this see page 122 and ff.

The influence of organic matter. The major agency in the encouragement of granulation probably is organic matter, especially as it undergoes decay and is gradually synthesized into humus. Not only does it bind but it lightens and expands, making possible the porosity so characteristic of individual soil aggregates. Plant roots probably promote granulation as much or more by the decay of the distributed organic matter as by the disruptive action of their ramifications. The electrochemical properties of the humus, as well as of the clay are probably effective in the organization and the later stabilization of the aggregates. Moreover, some investigators[30] maintain that at times slime and other viscous microbial products greatly encourage crumb development and exert a stabilizing influence as well. Granulation thus assumes a highly biological aspect.

Organic matter is of much importance in reducing the over-all plasticity and cohesion of the soil mass. In other words, it definitely modifies the effects of clay. In fact, some suspect that an actual chemical union may at times take place between the decaying organic matter and the silicate molecules. Moreover, the high adsorptive capacity of humus for water tends to intensify the disruptive effects of temperature changes and moisture fluctuations. The granulation of a clay soil apparently cannot be promoted adequately without the presence of a certain amount of humus. The maintenance of organic matter and of its synthesized products, therefore, is of great practical concern, not only chemically and biologically but physically as well (see Fig. 3:9).

The effect of adsorbed cations. One of the outstanding characteristics of the colloidal substances of the soil, both mineral and organic, is the ability to adsorb cations. (See page 81.) Moreover, the domination or even partial domination of certain of these cations tends to develop more or less definite physical characteristics. For instance, the adsorption of calcium and certain other ions may encourage granulation by a phenomenon called *flocculation*. When this occurs, the colloidal matter is coagulated and a localization occurs. This brings the colloidal material together in floccules and tends to encourage a type of structure that is quite desirable. Flocculation in itself, however, is not granulation as it usually does not

[30] Hubbell, D. S., and J. E. Chapman, "The Genesis of Structure in Two Calcareous Soils," *Soil Sci.*, 62: 271–281, 1946.

Martin, James P., "Microorganisms and Soil Aggregation, I. Origin and Nature of Some of the Aggregating Substances," *Soil Sci.*, 59: 163–174, 1945.

Myers, H. E., and T. M. McCalla, "Changes in Soil Aggregation in Relation to Bacterial Numbers, H-ion Concentration and Length of Time Soil Was Kept Moist," *Soil Sci.*, 51: 189–199, 1941.

provide for the stabilization of the aggregates. When such means are present and active as often is the case, flocculation assumes considerable practical significance.[31]

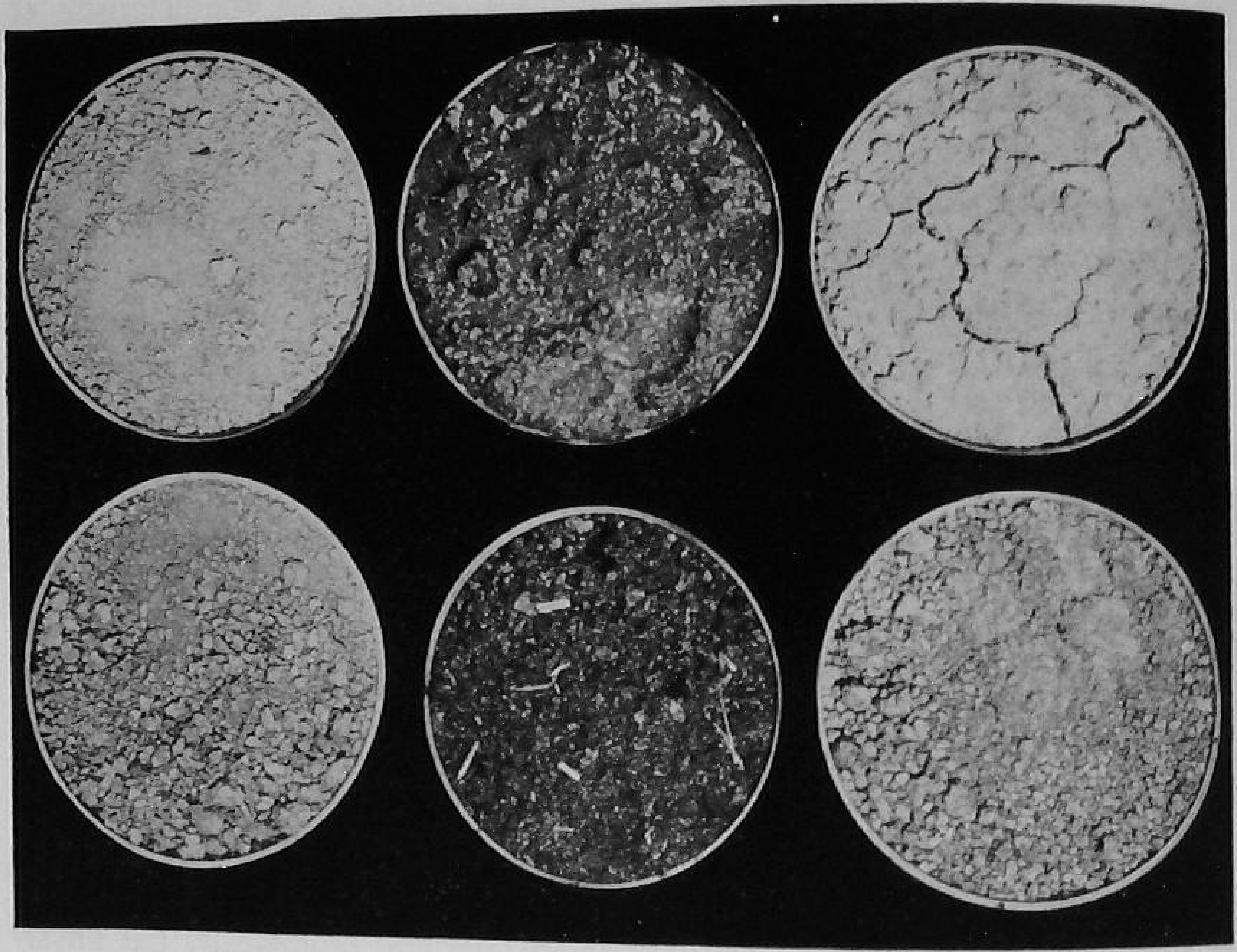

FIG. 3:9. *The effect of organic matter on the stability of soil structure. The upper three containers (left to right) show a granulated Brookston Clay (3 per cent organic matter) before and after wetting and after drying in the laboratory. Another sample of Brookston Clay high in organic matter (11 per cent) was given the same treatments (lower three containers).*

Note the instability of aggregates of the low organic matter soil shown by its tendency to "puddle" when wet and to harden and crust over when dry. Contrast these properties with those of the high organic matter soil below. (Photo, taken at Ohio State University, courtesy P. J. Zwerman.)

While many soils highly charged with native calcium exhibit granulation to a marked degree, it must not be inferred that this effect is due entirely to the direct influence of the adsorbed calcium. Exchangeable cations merely modify the influence of other factors, especially the over-all effects of decaying organic matter. The addition of lime, therefore, is effective as a granulating agency largely through its influence on biotic forces.[32] More-

[31] The mechanics of flocculation are more fully considered on page 104.

[32] Browning, G. M., and F. M. Milam, "Effect of Different Types of Organic Materials and Lime on Soil Aggregation," *Soil Sci.*, 57: 91–106, 1944.

over, the amounts applied usually are too small to have much effect directly on structural condition and the form generally used is the slower acting carbonate. Nevertheless, the consistent use of lime may tend to maintain, if not to increase, the granular condition of arable lands.

Influence of tillage. Some readers may be surprised that plowing and cultivation are not listed as major factors in the granulation of arable soils. It cannot be denied that the soil is loosened and aerated, especially by plowing, that the organic matter is mixed thereby with the mineral constituents, and that conditions are made more favorable for the activity of the natural forces of granulation. Nevertheless, plowing and cultivation in most cases seem only to make more noticeable the aggregation already attained. Other than this, tillage may even impair soil structure by purely mechanical means. In fact, land long under cultivation usually shows a decrease in granulation. This is partly because of a reduction in organic matter and partly, perhaps, because of the direct disruptive influence of tillage upon the soil aggregates. For example, the compaction that soils suffer from repeatedly running over the fields with heavy farm implements is by no means slight. An indication of the effect of such traffic upon bulk density and macro pore space is given in Table 3:8.

Table 3:8. The Packing Effect of Tractor and Sprayer Wheels as Measured by Bulk Density and Macro Pore Space [33]

Implement Wheel	*Bulk Density gm/cc*	*% Macro Pore Space*
Check—no packing	1.25	37.6
Tractor (cultivating)	1.32	35.0
Tractor & Potato Sprayer	1.46	27.0

A comparison of a virgin Putnam silt loam of Missouri [34] with its cultivated equivalent showed that cropping for sixty years had resulted in a

Ackerman, F. G., and H. E. Myers, "Some Factors Influencing Aggregation of Clay-pan Soils," *Soil Sci.*, 55: 405–413, 1943.

Metzger, W. H., and J. C. Hide, "Effect of Certain Crops and Soil Treatments on Soil Aggregation and the Distribution of Organic Carbon in Relation to Aggregate Size," *Jour. Amer. Soc. Agron.*, 30: 833–843, 1938.

[33] From Klute, A., and W. C. Jacob, "Physical Properties of Sassafras Silt Loam as Affected by Long-time Organic Matter Additions," *Proc. Soil Sci. Soc. Amer.*, 14: 24–28, 1949.

[34] Jenny, Hans, *Soil Fertility Losses Under Missouri Conditions*, Bul. 324, Missouri Agr. Exp. Sta., 1933. See also Baver, L. D., *Soil Physics*, John Wiley and Sons, Inc., New York, 1948, p. 181.

38 per cent reduction in organic matter and a 28 per cent decrease in large sized granules.[35] Soil granulation seems, therefore, to be determined not only by the effective control of organic matter but also by the application of tillage in such a way as to reduce granule destruction to a minimum.

Aggregate stability. One structural feature of great practical importance but not as yet adequately stressed, should receive due attention—aggregate stability.[36] Some granules readily succumb to the beating of rain and the rough and tumble of plowing and fitting of the land. Others, in contrast, resist disintegration tenaciously, thus making the maintenance of a suitable soil structure comparatively easy. Such differences arise because structural synthesis and the nature of the resulting aggregates fluctuate with the kind and amount of humus present and also with the type of mineral matter undergoing structural modification. Thus, the kind of clay segregated in the granules may well be a factor in determining their stability.

As a general rule the larger the aggregates present in any particular soil, the lower is their stability. This accounts for the difficulty encountered in cultivated land of building up soil aggregation beyond a certain size of granule or crumb.

3:11. THE STRUCTURAL MANAGEMENT OF SOILS

Light soils. The lack of inorganic colloidal matter in sandy soils has certain obvious advantages. Looseness, friability, good aeration and drainage, and easy tillage are characteristic. On the other hand, such soils are often too loose and open, and lack the capacity to adsorb and hold sufficient moisture and nutrients. They are, as a consequence, likely to be droughty and lacking in fertility. They need granulation. There is only one method of improving, in a practical field way, the structure of such a soil—the addition of organic matter. Organic material, if it undergoes favorable decomposition when incorporated with the soil, will not only act as a binding agent for the particles but will also increase the water-holding capacity.

[35] For a discussion of the techniques employed in the determination of the degree of water stable aggregation, see: Baver, L. D., *Soil Physics*, John Wiley and Sons, Inc., New York, 1948, pp. 172–177.

[36] Wilson, H. A., Roger Gish, and G. M. Browning, "Cropping Systems and Season as Factors Affecting Aggregate Stability," *Proc. Soil Sci. Soc. Amer.*, 12: 36–43, 1947.

Alderfer, R. B., "Seasonal Variability in the Aggregation of Hagerstown Silt Loam," *Soil Sci.*, 62: 151–168, 1946.

Baver, L. D., *Soil Physics*, John Wiley and Sons, Inc., New York, 1948, pp. 168–170.

AG51

The maintenance of a soil in sod is recognized the world over as a highly effective means of promoting granulation. The enmeshing effect of the ramifying roots as well as the tendency for humus to accumulate under this type of cropping has been used for centuries, unknowingly perhaps, to encourage and maintain a favorable soil structure. Farm manure and green manures, while markedly less effective, tend in the same direction. It should also be remembered that the canopy effects of sod and other crops as well as the protective capacity of artificial mulches of various kinds shelter the soil from dashing rains. This beating action often seriously impairs granulation, not only by carrying the granules away but also by pounding them to pieces (see Fig. 9:8 and page 260).

Heavy soils. The structural management of a silicate clayey soil is not such a simple problem as that of a sandy one. In the latter, the plasticity and cohesion are never great due to low content of inorganic colloids. In clays and similar soils of temperate regions, however, the potential plasticity and cohesion are always high due to the presence of large amounts of complex hydrated aluminum silicates in a colloidal condition. The more plastic such a soil becomes, the more likely it is to *puddle,*[37] especially if worked when wet. Moreover, a soil of high plasticity is prone, especially if puddled, to become hard and cloddy when dry, due to the cohesive tendencies of the small plate-like, viscous particles. Such soils must, therefore, be treated very carefully, especially in tillage operations (see Fig. 3:9). If plowed too wet, the aggregation of particles is broken down, and an unfavorable structure is sure to result. On the other hand, if plowed too dry, great clods are turned up which are difficult to work down into a good seedbed. In sandy soils and the so-called hydroxide clays of the tropics [38] such difficulties usually are at a minimum.

Not only must tillage operations be carefully timed in a heavy soil but granulation should be encouraged to the fullest degree. As already emphasized, organic matter is a major concern. In this respect sod crops, espe-

[37] When a surface soil in a plastic condition has been worked until its pore space is much reduced, it becomes practically impervious to air and water, and is said to be *puddled.* The presence of gelatinous and viscous colloidal materials seems to be the controlling factor in such a condition, the pore spaces of a puddled soil being filled with such material. When a soil in this condition dries, it usually becomes hard and dense.

[38] Much less trouble is encountered with the hydrated iron and aluminum oxide clays of the tropics and semi-tropics as their normal granulation usually is pronounced and rather stable. This is fortunate as it generally is extremely difficult to maintain any amount of organic matter in these soils when they are under cultivation. See page 347.

cially deep-rooted legumes, should be utilized to the fullest extent and the rotation planned to attain their maximum benefits. Most crops of a sod nature not only protect the land from dashing rains and erosion but also may actually promote an increase in soil organic matter. They therefore encourage granulation. Others, especially intertilled crops such as corn, potatoes, and cotton, have opposite effects. Aggregation is likely to deteriorate under their regime. A good rotation should so balance these opposing influences as to maintain satisfactory soil structure.

In confirmation of the above commonly accepted observations note the data shown in Table 3:9. A Marshall silt loam on the United States Soil Conservation farm near Clarinda, Iowa, was used, the cropping system employed having been in operation for a sufficient number of years for differences in their effects, if any, to develop. The water-stable aggregation under four crops was investigated in midsummer, usually the season of maximum granulation.

Table 3:9. Percentage Water-Stable Aggregation of a Marshall Silt Loam near Clarinda, Iowa, under Different Cropping Systems.[39] Samples Were Taken in August.

Crops	*Per Cent of the Water-stable Aggregates Which Were:*	
	Large (1 mm. and above)	*Small (Less than 1 mm.)*
Corn continuously	8.8	91.2
Corn in rotation	23.3	76.7
Meadow in rotation	42.2	57.8
Bluegrass continuously	57.0	43.0

A glance at the table will confirm the degranulating influence commonly ascribed to corn, less rapid, of course, when the crop is grown in a suitable rotation. The aggregating tendency of sod whether it is a meadow mixture or a bluegrass sward is likewise obvious. The data also suggest the degrees of soil granulation a person may normally expect and disclose the rapidity with which aggregation may decline, the individual clumps becoming smaller and smaller as degradation progresses. Certainly granulation is a fluctuating, ever-changing property and deserves more attention in practice than it generally receives.

[39] Wilson, H. A., Roger Gish and G. M. Browning, "Cropping Systems and Season as Factors Affecting Aggregate Stability," *Proc. Soil Sci. Soc. Amer.*, 12: 36–43, 1947.

3:12. TILTH AND TILLAGE[40]

Although frequent mention has been made of plowing and cultivation in relation to soil structure, something must be said regarding seedbed[41] preparation and the maintenance of its granulation throughout the season. A convenient term—*tilth*—will greatly facilitate such a discussion, which of necessity must be brief.

Tilth defined. Simply defined tilth refers to "the physical condition of the soil in its relation to plant growth" and hence must take cognizance of all physical conditions that influence crop development.

Not only does tilth depend on granulation and its stability, but also on such factors as moisture content, degree of aeration, rate of water infiltration, drainage, and capillary water capacity. As might be expected, it often changes rapidly and markedly. For instance, working properties, which are an expression of tilth, may be altered abruptly, especially with heavy soils, by a slight change in moisture.

One of the objectives of plowing and cultivation supposedly is the encouragement and maintenance of good tilth. Unfortunately, however, especially when improperly administered, these operations may seriously impair tilth directly or set the stage for later deterioration.[42] Let us consider the situation briefly.

Tilth and plowing. The mold-board plow is a tillage implement designed, through years of experimentation, to accentuate the granulation of the soil by its lifting, twisting, and shearing actions. At the same time it turns under, by the inversion or partial inversion of the furrow-slice, any organic residues that may be on or in the surface.[43] It is a powerful tool

[40] For a more detailed coverage of these phases, see: Baver, L. D., *Soil Physics*, John Wiley and Sons, Inc., New York, 1948, Chap. 4.

For a good review of literature respecting soil changes induced by tillage consult: Whiteside, E. P., and R. S. Smith, "Soil Changes Associated with Tillage and Cropping in Humid Areas of United States," *Jour. Amer. Soc. Agron.*, 33: 765–777, 1941.

[41] Seedbed is used here as referring to a full-depth furrow-slice and not merely to the surface 2 or 3 inches involved in seed germination.

[42] The measurement of soil tilth is extremely difficult since it is such an indefinite condition influenced by so many rather illusive factors. The nature and degree of granulation as well as resistance to carefully controlled penetration tests are the criteria so far utilized. For the procedure in respect to the latter see: Richards, S. J., "A Soil Penetrometer," *Proc. Soil Sci. Soc. Amer.*, 6: 104–107, 1941.

[43] An interesting suggestion has been made by a Russian investigator in respect to the benefits of plowing. The granulation of the surface layer of tilled land may be impaired by cultivation, the beating of rain and by other causes, while the aggregation of the lower half of the seedbed is likely to be maintained or even enhanced by root

for good when properly used—*for ill* if it is not well adjusted or if applied under unsatisfactory conditions. Undoubtedly, it is the best implement available for the preparation of sod land for cultivated crops. It cuts through the matted roots, turns the sod and aftermath into the furrow, and exposes the shattered, subsurface layers for further preparation.

On heavy soils, especially if imperfectly drained, the plow is indispensable if maximum crop yields are to be attained.[44] On light soils, however, the advantage of the mold-board plow is not so obvious as disking or some other type of cultivation may be as good or even better especially if a stubble mulch [45] is desired as is often the case in areas of low rainfall.

Undoubtedly many farmers plow too much and at times when soil aggregation is seriously impaired. This is likely to be the case when clayey soils are plowed too wet or too dry. Yet in spite of its misuse and the criticism [46] leveled at it, the plow continues to be an important factor in the structural management of land and the maintenance of crop yields. This is clearly shown by the data of Table 3:10. When and how to plow, in this age of heavy mechanized farm implements, are more important than ever before.

Tilth and cultivation. In respect to possible misuse, cultivation is more likely to impair tilth than is plowing. It is employed more frequently during the rotation, is performed by many types of implements, and drastically influences the upper furrow-slice that is so susceptible to degranulation. Hence, in the preparation of a seedbed only the minimum of cultivation should be applied after plowing, leaving the soil with a granular structure suitable for seeding yet coarse enough at the surface to resist erosion and the puddling effects of beating rains.

Coarse granules at the soil surface in the spring, even though greatly

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ramification and decay. Its tilth is therefore comparatively high. Plowing, by reversing these zones, tends to keep the tilth of the surface at a higher level, at the same time placing the soil previously exposed in a position where the damaged granulation may be repaired. See Williams, W. R., "Theses of Tenacity and Cohesion in Soil Structure," *Pedology*, 30 year: 755–762, 1935.

[44] Browning, G. M., and R. A. Norton, "Tillage Practices with Corn and Soy Beans in Iowa," *Proc. Soil Sci. Soc. Amer.*, 12: 491–496, 1947.

[45] Duley, F. L., and J. C. Russel, "Machinery Requirements for Farming through Crop Residues," *Agr. Eng.*, 23: 39–42, 1942.

[46] For a drastic criticism of the plow, with which most agronomists by no means wholly agree, see: Faulkner, E. H., *Plowman's Folly*, Univ. Oklahoma Press, Norman, Okla., 1943. For a more studied concept, consult Norton, R. A., E. V. Collins, and G. M. Browning, "Present Status of the Plow as a Tillage Implement," *Agr. Eng.*, 25: 7–10, 1944.

Table 3:10. Data Showing the Influence of Various Methods of Seedbed Preparation upon Soil Porosity and Yields of Unfertilized Corn in Ohio[47]

Seedbed Preparation[48]	*After Seven Years* Total Porosity %	Air Space Porosity %	*Yield of Corn in Bus. per Acre, Average of Eight Years*
1. Standard	56.3	25.9	46.7
2. Sod plow	56.0	24.9	47.2
3. Rotary tillage	56.9	24.2	42.1
4. Subsurface tillage	54.8	19.2	39.1
5. Surface tillage only	49.1	14.2	34.5
6. Standard plus straw mulch	55.8	26.9	50.5

degraded by autumn, may insure a satisfactory tilth through the critical portion of the growing season. The influence of a seedbed thus prepared usually greatly affects crop yield. Corn, for instance, is a plant that markedly responds to the persistence of good tilth. For the influence of various methods of seed-bed preparation upon soil porosity and corn yields, see Table 3:10. The deductions are obvious.[49]

Cultivation during the growing season serves mainly to break up crusts induced by dashing rains, to insure adequate aeration and to kill weeds. When herbicides are used, the control of weeds by cultivation ceases to be so important. With intertilled crops cultivation should be kept at a minimum and ordinarily should not extend much beyond midseason. This is because serious root-pruning (see Fig. 8:3) may occur as well as a loss of water by evaporation from the exposed surfaces[50] without a compensating improvement in tilth. In fact, cultivation at best usually impairs, di-

[47] Page, J. B., C. J. Willard, and G. W. McCuen, "Progress Report on Tillage Methods in Preparing Land for Corn," *Proc. Soil Sci. Soc. Amer.*, 11: 77–80, 1945.

[48] 1. The usual fitting methods employed for corn in Ohio, that is, plowing and harrowing.
2. Furrow-slice completely inverted with sod-plow.
3. Over-preparation with rotary tiller.
4. Subsurface tillage—corn planted under trash mulch.
5. Very slight surface tillage—enough to kill weeds.
6. Heavy straw mulch applied after first cultivation of corn.

[49] For a consideration of seedbed preparation see: Slipher, J. A., "The Mechanical Manipulation of the Soil as It Affects Structure," *Agr. Eng.*, 13: 7–10, 1932. And Russell, E. W., and B. A. Keen, "Studies in Soil Cultivation. VII. The Effect of Cultivation on Crop Yields," *Jour. Agr. Sci.*, 28: 212–233, 1938.

[50] The seriousness of root-pruning and the water losses due to cultivation in soil-mulch establishment are discussed in some detail on pages 230 and 233.

rectly and indirectly, soil aggregation. Hence, the newly prepared seedbed, as already suggested, should present a coarsely granulated surface layer and dependence placed upon the adequate persistence of this structural condition throughout the growing season. Do not hasten the decline of tilth by too much cultivation.

CHAPTER

4

Soil Colloids. Their Nature and Practical Significance

IT HAS already been emphasized that the most active portions of the soil are those in the colloidal state [1] and that the two distinct types of colloidal matter, mineral and organic, exist in intimate and heterogeneous intermixture. The former type of colloidal matter is present almost exclusively as clay of various kinds while the latter is represented by humus.

Both of these groups are the seat of such varied and vigorous changes that they deserve diligent study. In fact, most investigators feel that many problems dealing with the normal functioning of this natural body we call the soil will not be fully understood until we know more about the soil colloids.[2] Attention will be focused to begin with on the inorganic

[1] The colloidal state refers to a two-phase system in which one material (or materials) in a very fine state of aggregation, approaching but not attaining a molecular subdivision, is heterogeneously dispersed through a second. Each of the two phases of a colloidal system may be a solid, liquid, or gas. All combinations are colloidally possible except a gas dispersed in a gas. Good examples of the colloidal state are milk and cheese, clouds and fog, starch, gelatin, pectin, rubber, blood, proteins, plant and animal cells (both contents and cell wall), and of course soil. Obviously, the colloidal state in nature is the rule rather than the exception.

Materials in this state are distinguished especially by three properties—(1) great effective *surface* or interface, (2) capacity to *fix* and hold solids, gases, salts, and ions, and (3) *catalysis*, the tendency to hasten or retard chemical reactions.

[2] The literature dealing with soil colloidal matter is exceedingly voluminous. Perhaps the best beginning can be made with Marshall, C. E., *The Colloidal Chemistry of Silicate Minerals*, Academic Press, Inc., New York, 1949. Also see: Gieseking, J. E., "The Clay Minerals in Soils," *Advances in Agronomy*, Vol. I: 159–200, A. G. Norman, Ed., Academic Press Inc., 1949. The following general article is in many ways very enlightening: Kelly, W. P., "Modern Concepts of Soil Science," *Soil Sci.*, 62: 469–476, 1946. Also see: Russell, E. J., and E. W. Russell, *Soil Conditions and Plant Growth*, Longmans, Green and Company, New York, 1950, Chaps. 7 and 8.

colloidal matter, leaving that of organic origin for later consideration. (Pages 158 and 160.)

Size of mineral colloidal particles. Before dealing with the specific properties of mineral colloids it may be well to define a little more clearly the actual fraction of the soil which is in the colloidal state. It is generally considered that the upper limit in size of the mineral colloidal particles is not greater than .001 mm. or one micron (μ). In fact, in most cases the upper limit is considered to be as low as 0.5 or even 0.2 microns.

As was pointed out in Chapter 3 (page 46) the maximum size limit of the *clay* fraction of a soil is considered as .002 mm. or 2μ. Thus by no means all of the clay is strictly colloidal, and to so consider it is technically incorrect. Nevertheless, in ordinary parlance such a use is permissible and will be thus employed subject to the error pointed out.[3]

In a broad way, two groups of clays are recognized—the *silicate clays* so characteristic of temperate regions, and the *iron* and *aluminum hydrous oxide clays* found in the tropics and semi-tropics. Our concern for the immediate present will be with the silicates since they dominate the great agricultural regions of the world.

4:1. THE GENERAL CONSTITUTION OF SILICATE CLAYS

Shape. Early students of clayey colloidal matter visualized the individual particles as more or less spherical. However, it is now definitely established [4] that the particles are laminated, that is made up of layers of plates or flakes (see Fig. 4:1). Their individual size and shape depends upon their mineralogical organization and the conditions under which they have developed. Some of these particles are mica-like and definitely hexagonal; others are irregularly plate- or flake-like; while still others seem to be lath-shaped blades or even rods. With some particles the edges seem to be clean-cut while with others the appearance is indistinctly frayed or fluffy. (See Fig. 4:6 page 103.) In all cases, however, the horizontal extension of the individual particles greatly exceeds their vertical dimension.[5]

[3] In any investigation of colloidal clay the upper limit of particles size should be low enough to insure a fraction that is wholly colloidal and whose physical and chemical properties are fairly constant. This should be attained by setting the upper size-limit at .10 or .20μ (100 or 200 mμ).

[4] See: Shaw, B. T., and R. P. Humbert, "Electron Micrographs of Clay Minerals," *Proc. Soil Sci. Soc. Amer.*, 6: 146–149, 1941. Also, Marshall, C. E., *The Colloidal Chemistry of the Silicate Minerals*, Academic Press, Inc., New York, 1949.

[5] The flat, mica-like shapes that commonly characterize clay particles can be

Each clay particle regardless of its individual shape is made up of a large number of plate-like structural units. The arrangement is very much like that of a piece of mica—the leaves of the latter representing the plate-like units of which the clay particles are composed. (See Fig. 4:1.) These units are held together with varying degrees of tenacity, depending on the particular type of colloid. In some cases expansion between loosely held units occurs upon wetting, causing an over-all swelling of the clay particles. In other clays the plates are held more rigidly and little expansion occurs.

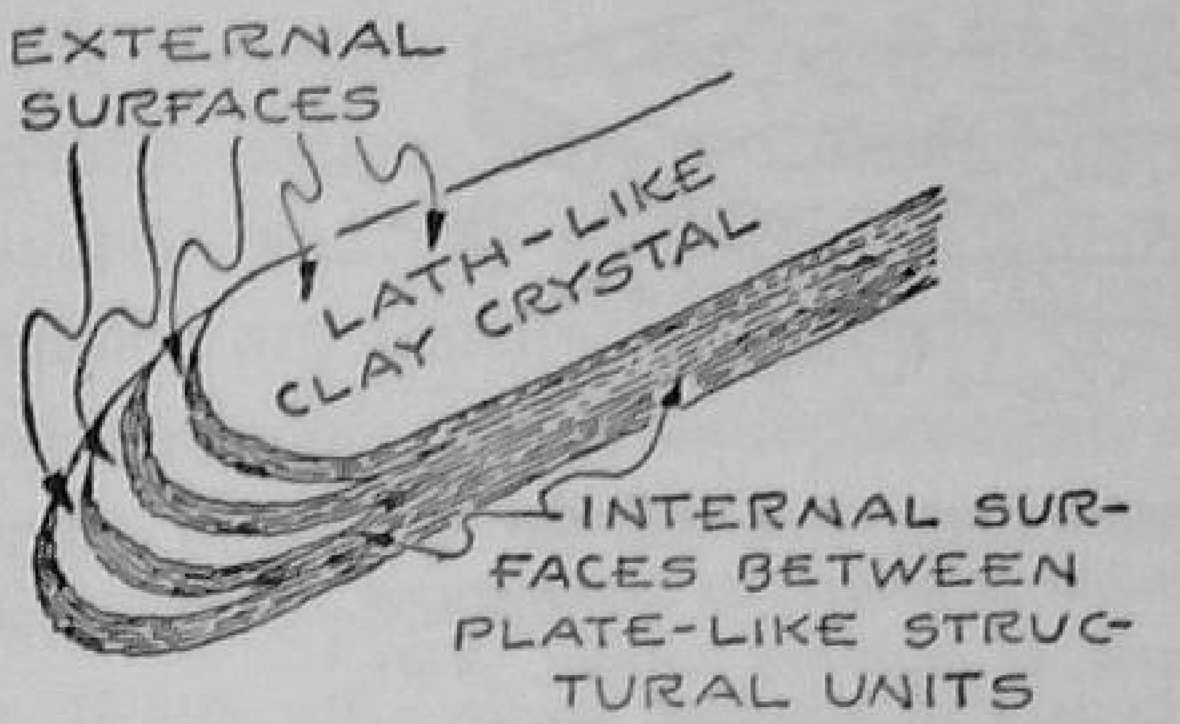

FIG. 4:1. *A generalized representation of a lath-shaped clay crystal showing its plate-like structure. Two types of surfaces are evident*—external *and* internal. *The latter is much more extended than the former and, except for kaolinite and similar clays, is much more important in respect to adsorptive capacity than are the external surfaces.*

Surface area. As is readily anticipated, clay particles, merely because of their fineness of division, must expose a large amount of *external* surface. But this is by no means all. There are *internal* surfaces as well. This internal interface occurs between the plate-like crystal units that make up each particle. (See Fig. 4:1.) Thus the tremendous surface area that characterizes clay is accounted for not only by fineness of division but also by the plate-like structure of the tiny particles. As a conservative estimate, it is suggested that the active interface due to the clay fraction of an acre-furrow-slice of a representative silt or clay loam soil probably exceeds the land area of Illinois or Florida at least forty or fifty times.

Electronegative charge and adsorbed cations. The minute silicate clay colloids are electrically active, each particle ordinarily being *negatively* charged. As a consequence, thousands of positively charged ions or *cations* are attracted to each colloidal crystal. This gives rise to what is known as an ionic double layer. (See Fig. 4:2.) The colloidal particle constitutes the *inner* ionic layer, being essentially a huge *anion,* the surfaces of which

demonstrated in this simple way. By rotating a suitable clay suspension, the particles in motion are oriented temporarily in the same direction and as a result eddies and currents are clearly apparent as the light is reflected from the faces of the symmetrically arranged crystals. When the particles are at rest, they lose this orientation, the reflection becomes uniform and the eddies disappear. A suspension of round particles, of course, will not show the phenomenon just described.

are highly negative in charge. The *outer* ionic layer is made up of a swarm of rather loosely held cations which surround and penetrate the particle. Thus when a clay particle moves through its dispersive medium it is accompanied by a tremendous number of adsorbed cations.

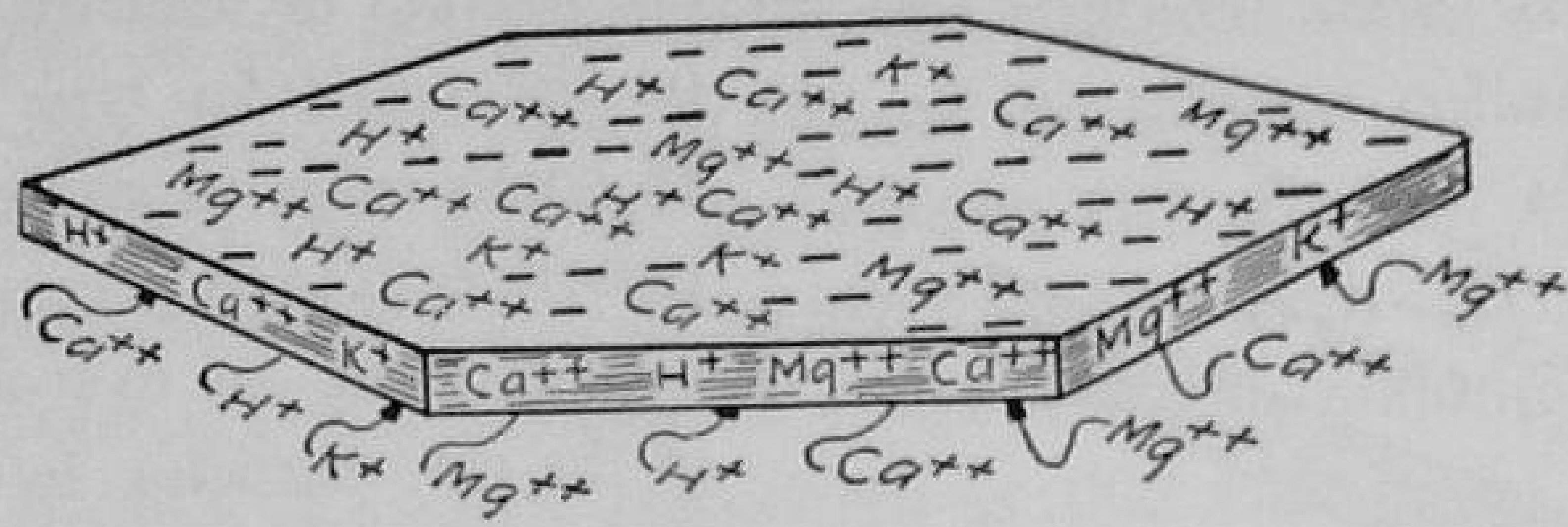

FIG. 4:2. *Diagrammatic representation of a colloidal clay crystal (micelle) with its sheet-like structure, its innumerable negative charges, and its swarm of adsorbed cations. Note that Ca-ions are dominant, but that some H-, K-, Mg- and Na-ions are present. No attempt has been made to show the adsorption of cations within the crystal (that is, between the plate-like crystal units) or the numerous molecules of water that are held by the crystal surfaces and by the individual cations (hydrated ions).*

Since the charges on the individual crystals are normally negative[6] these crystals function somewhat like a simple acid radical such as Cl^- or $SO_4^=$ and will migrate to the positive pole when subjected to an electrical current. For convenience in designation the individual crystalline particle is spoken of as a *micelle,* or a nucleus.

Associated with the layer of cations that throng the adsorptive surfaces of clay particles is a large and indefinite amount of water. Part of these water molecules is carried by the adsorbed cations mentioned above since most of them are definitely hydrated.[7] In addition, all silicate clays hold water molecules at their external faces. Moreover, many clays hold numberless water molecules packed between the plates that make up the clay

[6] Why the crystal usually carries a negative charge is explained later. (See page 93.)

[7] It is now agreed that cations are commonly surrounded by water molecules. These are held electro-statically and greatly influence the closeness with which the cations may contact surfaces. Na- and K-ions apparently are highly hydrated. Ca- and Mg-ions also carry water molecules but not in the amounts that apparently characterize the alkali ions.

According to Remy, the order for the monovalent ions in respect to hydration is Na > K > H. For the divalent ions Mg > Ca. See Gortner, R. A., W. F. Hoffman and W. B. Sinclair, "Physico-Chemical Studies on Proteins, III. Protein and Lyotropic Series," *Colloidal Symposium Monograph,* 5: 179–198, 1928.

micelle. These various types of water *in toto* are referred to when the hydration, or the water-adsorptive capacity of clays, is under consideration.[8]

4:2. THE ADSORBED[9] CATIONS

It is evident from the foregoing discussion that clay particles present a system composed of two distinct parts: (1) a relatively large insoluble *micelle,* and (2) a loosely held swarm of *cations.* Since these adsorbed cations are usually rather easily displaced, they are also spoken of as *exchangeable ions.* This replacement, called *cation exchange,* is one of the most important of all soil phenomena. It will be considered in detail later. (See page 97.)

While all cations may be adsorbed by clay micelles, certain ones are especially prominent under natural conditions. For humid region colloids these in the order of their numbers are H^+ and Ca^{++} first, Mg^{++} second, and K^+ and Na^+ third. For well-drained arid-region soils, the order of the exchangeable ions is usually Ca^{++} and Mg^{++} first, Na^+ and K^+ next, and H^+ least. The humid region clays are considered as having a calcium-hydrogen complex, while those in arid regions are dominated by calcium and magnesium.[10]

When the drainage of an arid-region soil is impeded and alkaline salts accumulate, adsorbed Na-ions are likely to equal or even exceed those of the adsorbed Ca. Here then would be a sodium or a sodium-calcium complex. By the same rule in humid regions the displacement of the metallic cations by H-ions gives a hydrogen or an acid clay. Since the cation, or cations, preponderant in a colloidal system has much to do with its physi-

[8] Two types of water of hydration are conceived—*broken-bond* and *planar.* In the former case the dipolar water molecules apparently are oriented and held by the unsatisfied valence bonds existing along the edges of the clay crystals where the ends of the flat structural units are exposed. (See Fig. 4:2.) Such water of hydration is very tightly held and is comparatively small in amount.

The water molecules of the planar type are, in contrast, oriented in the free electrical fields that seem to exist on the crystal surfaces, both those externally exposed and those located internally. This type of adsorbed water is comparatively large in amount, is loosely held, most of it being easily expelled by heating at low temperatures. It is not all released, however, at 110° C, the temperature to which a sample of soil usually is heated in making a moisture determination. See: Kelley, W. P., Hans Jenny, and S. M. Brown, "Hydration of Clay Minerals and Soil Colloids in Relation to Crystal Structure," *Soil Sci.*, 41: 259–274, 1936.

[9] For a definition of adsorption see note on page 35.

[10] Other exchangeable cations that may be present but usually in small amounts are those of iron, aluminum, manganese, zinc, and ammonium.

cal and chemical properties as well as its relationship to plants, this phase of the subject is of tremendous practical importance.

As mentioned above, calcium and magnesium are the adsorbed metallic cations held in largest amounts by the siliceous clays of most humid region soils. Exchangeable potassium is, in most cases, sparingly present. The data in Table 4:1 are representative of a considerable amount of information available respecting this relationship.

Table 4:1. Relative Proportion of Adsorbed Metallic Cations Present in Certain Surface Soils of the United States. (The percentage figures in each case are based on the sum of the metallic cations taken as 100. Note the geographic distribution of the soil samples.)

Soils	*Sum of Metallic Cations Taken as 100*			
	Ca	Mg	K	Na
Penn Loam (N.J.)[11]	60.8	15.8	19.0	4.4
Mardin Silt Loam (N.Y.)[12]	90.7	5.0	3.1	1.2
Webster Series Soil (Ia.)[13]	76.8	20.4	1.2	1.6
Sweeney Clay Loam (Calif.)[14] (prairie)	76.1	21.3	1.3	1.3
Red River Valley Soil (Minn.)[15] (Free of soluble salts)	73.9	21.5	4.2	.4
Keith Silt Loam (Nebr.)[16] (Chestnut)	77.1	13.3	7.1	2.5
Holdrege Silt Loam (Nebr.)[16] (Chernozem)	66.5	20.9	11.1	1.5

4:3. THE MINERALOGICAL ORGANIZATION[17] OF THE VARIOUS TYPES OF SILICATE CLAYS

For many years, even after its colloidal nature was recognized, clay was thought to be an amorphous body. X-rays as well as electron-micro-

[11] Prince, A. L., *et al.*, "Forty-year Studies of Nitrogen Fertilizers," *Soil Sci.*, 52: 247–261, 1941.

[12] Cope, J. T., unpublished thesis data, Cornell Univ., 1950.

[13] Bower, C. A., and W. H. Pierre, "Potassium Response of Various Crops on a High-lime Soil in Relation to Their Contents of Potassium, Calcium, Magnesium and Sodium," *Jour. Amer. Soc. Agron.*, 36: 608–614, 1944.

[14] Barshad, Isaac, "A Pedologic Study of California Prairie Soils," *Soil Sci.*, 61: 423–442, 1946.

[15] Rost, C. O., and K. A. Maehl, "Some Solodized Soils of the Red River Valley," *Soil Sci.*, 55: 301–312, 1943.

[16] Larson, W. E., *et al.*, "Characteristics of Three Soils from the Chernozem and Chestnut Soil Regions of Nebraska," *Proc. Soil Sci. Soc. Amer.*, 12: 420–423, 1947.

[17] For brief and clear consideration of the subject consult: Lutz, H. J., and R. F. Chandler, Jr., *Forest Soils*, John Wiley and Sons, Inc., New York, 1946.

scope examinations, however, show definitely that the clay particles, in spite of their inconceivable smallness, are definitely crystalline.[18] On the basis of their crystalline properties three general groups of silicate clays are now recognized: [19] (1) Kaolinite, (2) Montmorillonite, and (3) the hydrous micas, of which Illite is representative. The properties of these minerals will be considered in order.

Kaolinite group. The first group includes a number of clays—*kaolinite, halloysite, anauxite, dickite,* and several others. Of these kaolinite is of greatest importance in soils. The crystals of this mineral are plate-like in nature, being built up of flat crystal *units.* These units in turn are composed of alternate layers of *alumina* and *silica* sheets as shown by the drawing in Figure 4:3. Since every unit contains one each of the silica and alumina sheets, this group of clays are said to have a *1:1 type crystal* lattice.

The two sheets of each crystal unit of kaolinite are held together by oxygen atoms which are mutually shared by the silicon and aluminum atoms in their respective sheets. These units, in turn, are rather tenaciously held together by oxygen-hydroxyl linkages. (See Fig. 4:3.) Consequently, the lattice is *fixed* and no expansion ordinarily occurs between units when the clay is wetted. Therefore, cations and water enter between the structural units of the micelle with extreme difficulty if at all. The effective surface of kaolinite is thus restricted to its outer faces. As a result, its adsorptive capacity for cations is comparatively low.

Kaolinite crystals usually are roughly hexagonal with clean-cut edges. (See Fig. 4:6 page 103.) In comparison with montmorillonite particles they are large in size, the diameter generally ranging from 0.10 to 5 microns with the majority falling within 0.2 to 2 microns. Because of the tenacity with which their structural units are held together, kaolinite particles are not readily broken down into extremely thin sheets.

In contrast with the other silicate groups, the plasticity, cohesion, shrinkage, and swelling properties of kaolinite are very low. Its restricted inter-

[18] Kelley, W. P., "The Evidence as to the Crystallinity of Soil Colloids," *Trans. Third Internat. Cong. Soil Sci.*, 3: 88–91, 1935; and Shaw, B. T., "The Nature of Colloidal Clay as Revealed by the Electron Microscope," *Jour. Phys. Chemistry,* 46: 1032–1043, 1942.

[19] Methods for the identification and quantitative estimations of the various clays are complicated and technical. See: Hendricks, S. B., and L. T. Alexander, "Minerals Present in Soil Colloids, I. Descriptions and Methods for Identification," *Soil Sci.*, 48: 257–268, 1939; and Kelley, W. P., and J. B. Page, "Criteria for the Identification of the Constituents of Soil Colloids," *Proc. Soil Sci. Soc. Amer.*, 7: 175–181, 1942. The later paper carries a well selected bibliography.

face and limited adsorptive capacity for cations and water molecules have already been mentioned. In general kaolinite does not exhibit colloidal properties of a high order of intensity.

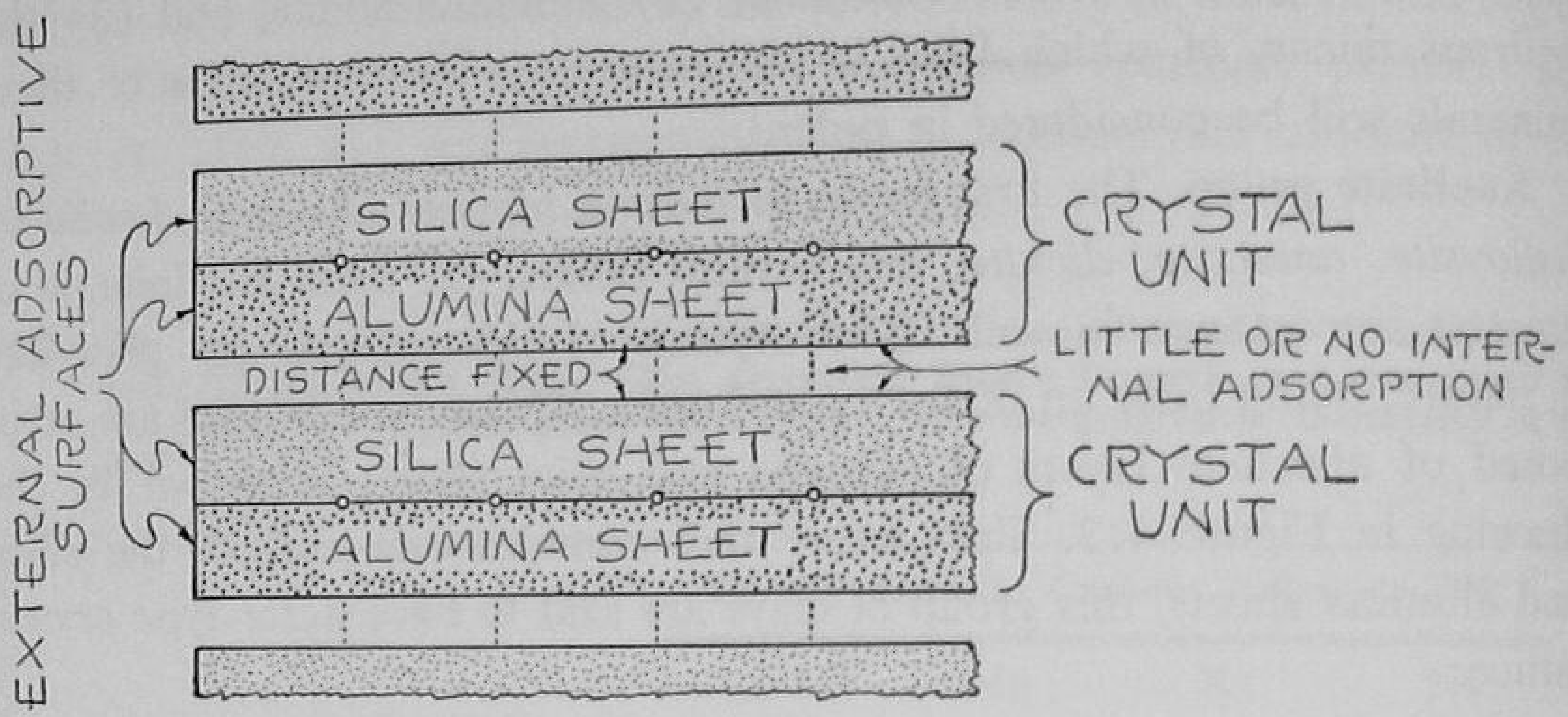

FIG. *4:3. A schematic diagram showing the lattice structure characteristic of kaolinite crystals. The section is a vertical one and gives an edge-wise view of two of the innumerable units that make up a crystal of this clay. Each of the crystal units is composed of one silica sheet and one alumina sheet (1 to 1 type of lattice) bonded very tightly by mutually shared oxygen atoms (represented by small circles).*

The respective crystal units are, in turn, bound to each other rather tightly by an oxygen-hydroxyl linkage (denoted by dots) thereby giving a restricted and non-expanding lattice. As a result, ions as well as water molecules penetrate the crystals with great difficulty, if at all. The adsorptive capacity of kaolinite is, therefore, limited almost entirely to the external surfaces of its crystals.

Montmorillonite group. The montmorillonitic group, like the kaolinitic, contains several clays, such as *montmorillonite, beidellite, nontronite,* and *saponite.* Of these the first is easily the most important although the others, especially beidellite, occur prominently in certain soils. The flake-like crystal units of montmorillonite (see Fig. 4:6) are made up of two silica sheets with an alumina sheet tenaciously bound in between by mutually shared oxygen atoms. (See Fig. 4:4.) The crystal lattice is, therefore, a *2 to 1 type.*

The structural units themselves, however, are so loosely held together by very weak oxygen-oxygen linkages that the crystal lattice is bellows-like and *expands* very readily. As a consequence, montmorillonitic crystals may be so easily fractured artificially as to give particles that approach the size of single structural units. Normally, however, montmorillonite crystals range in diameter from .01 to 2.0 microns. They are thus much smaller than the average kaolinite micelle.

Because of its easily expanded crystal lattice, cations and water molecules are able to move in between the crystal units of montmorillonite. Thus, in addition to the surface on the outside of the particle, *internal*

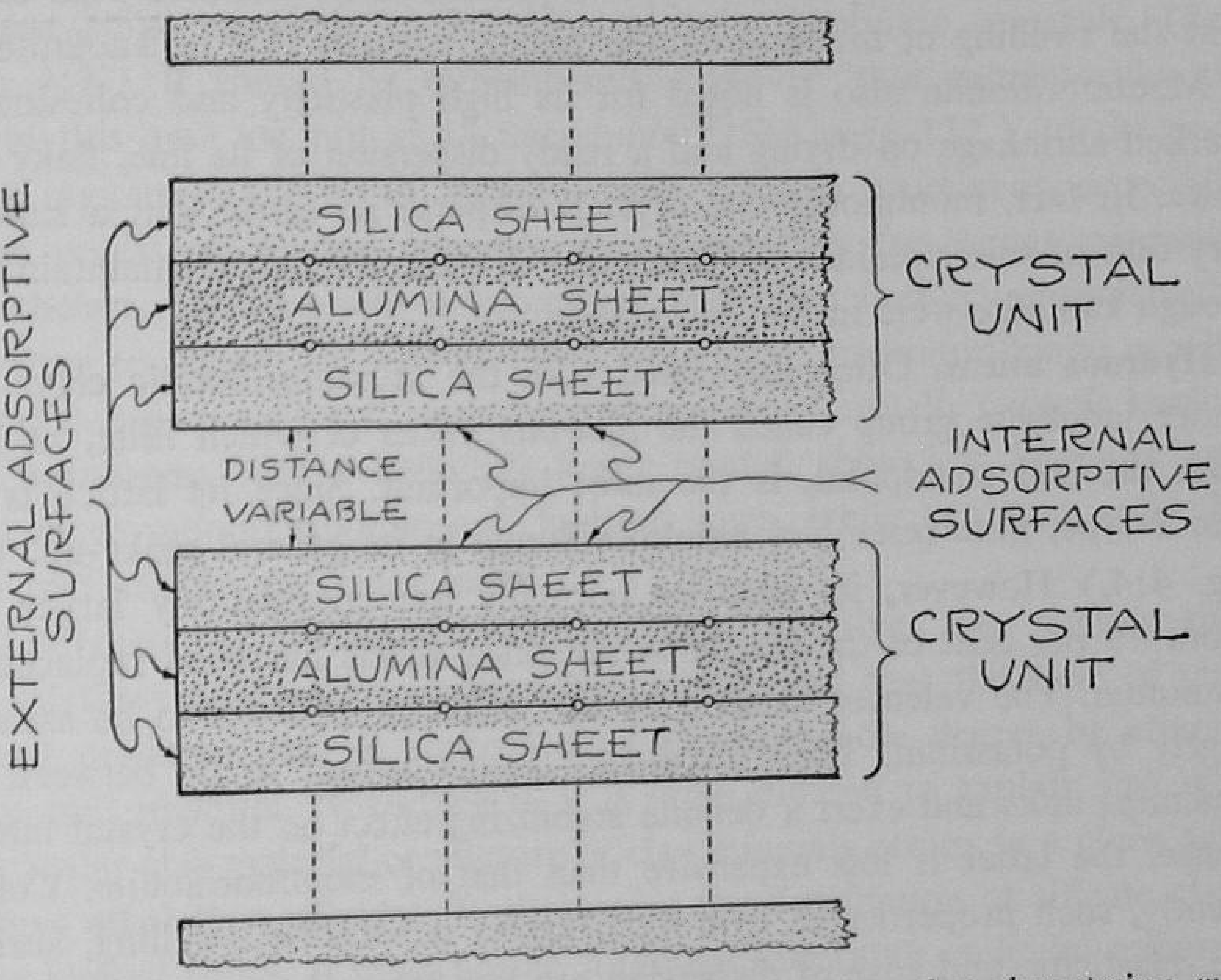

FIG. 4:4. *A schematic representation of the lattice structure that characterizes montmorillonite crystals. The section is vertical and provides an edge-wise view of two of the innumerable units that make up a crystal of this clay. Each crystal unit is composed of two sheets of silica and one of alumina (2 to 1 type of lattice) tightly bound together by mutually shared oxygen atoms (represented by small circles).*

The respective crystal units in turn are loosely bound to one another by weak oxygen linkages (represented by dots) which allow a ready and comparatively wide expansion of the lattice (quite in contrast to kaolinite). Not only do various cations as well as water molecules readily enter the crystals but the bellows-like spread of the lattice insures a very high internal adsorption, much greater than that ascribed to the external surfaces.

Illite has the same general structural organization as does montmorillonite except in respect to the linkages between the crystal units. Here potassium atoms supply additional connecting linkages between the crystal units, thus supplementing the oxygen bonding. These potassium linkages lessen the amount of expansion that the illite crystals are able to exhibit. As a result, the adsorptive capacity of this clay is considerably lower than that of montmorillonite. Illite, nevertheless, exceeds kaolinite in this respect.

surfaces of very much greater total magnitude are presented. This internal surface is also negatively charged.[20] Consequently, this 2:1 type of colloid surface is also negatively charged.

[20] The source of the charge of this and other minerals is discussed in section 4:6.

has a high cation adsorption capacity—perhaps 10 to 12 times that of kaolinite.

Moreover, because of the nature of the electrical field within the micelle, water of the planar [21] type is present in abundance. This means that the swelling of montmorillonite greatly exceeds that of kaolinite.

Montmorillonite also is noted for its high plasticity and cohesion, its marked shrinkage on drying and a ready dispersion of its fine, flaky particles. In fact, montmorillonite crystals disperse so easily that a satisfactory tilth of soils dominated by this clay is more difficult to maintain than though kaolinite were in the ascendancy.

Hydrous micas. Often associated with the montmorillonitic clays is a rather indefinite group called the *hydrous micas* of which illite, at least from the soil standpoint, is the most important. Since its lattice is the *2 to 1 type,* illite resembles montmorillonite in its general make-up. (See Fig. 4:4.) However, its particles normally are considerably larger and about 15 per cent of the silicon in the silica sheets has been replaced by aluminum. The valences vacated by this substitution seem to be satisfied largely by potassium. These potassium atoms appear to lie between the structural units and exert a definite stabilizing effect on the crystal lattice. Hence, the latter is less expansive than that of montmorillonite. Consequently, such properties as hydration, cation adsorption, swelling, shrinkage, plasticity, and ease of dispersion are less intensely developed. Nevertheless, illite excels kaolinite in respect to these characteristics. As to size, illite crystals are apparently intermediate between those of montmorillonite and kaolinite. Whenever unfertilized soils show an unusually high content of potassium, it is probable that illite makes up a goodly proportion of the clay present. For an electron micrograph of illite see Figure 4:6 on page 103.

4:4. GEOGRAPHIC DISTRIBUTION OF SILICATE CLAYS

As one might well surmise, the clay of any particular soil is made up, not of one mineral, but of a mixture of different colloidal minerals. Moreover, the mixture may vary from horizon to horizon often accompanied by a change in the dominating type. This occurs because the kind of clay that develops depends not only upon climatic influences and profile conditions but also upon the nature of the parent material. The situation may be further complicated by the presence in the parent material itself

[21] For a discussion of water of hydration see note at bottom of page 83.

of clays that were formed under a preceding and perhaps an entirely different type of climatic regime. Nevertheless, some very general deductions seem possible in respect to the soils of the United States.

Regional differences. It would seem in general that the clays in our southern soils are likely to be dominated by kaolinitic minerals. (See Table 4:2.) It should be remembered, however, that montmorillonitic soils in this area are not at all uncommon. (See page 112.) In the cool humid regions to the north, hydrous mica often is prominent, especially if high potassium-bearing minerals were present in the parent materials. Nevertheless, kaolinite still is prominent and often dominates such soils.

Shifting to the prairie soils of the Middle West, montmorillonite usually appears conspicuously and, with the hydrous micas, usually exceeds kaolinite. Chernozems with a definitely lower rainfall show less kaolinite and much more montmorillonite and hydrous mica, while in desert soils the latter two are definitely dominant.

While these conclusions are more or less tentative, they suggest that clay mixtures vary widely with different soils and that the type of clay mineral predominating is controlled to a considerable degree by climate and parent material. Nevertheless, it is often difficult to explain just why a particular clay material or mixture of clay minerals occurs in a given soil.

Clays other than silicates. In discussing the distribution of silicate clays in the United States, it must not be forgotten that other colloidal minerals besides the ones mentioned are present. These occur either as mere accessories or as an important part of the colloidal complex. Of the latter, the oxides of silicon, iron, and aluminum should be mentioned. While these occur frequently in temperate-region soils, the latter two are especially important in tropical and semi-tropical regions, giving rise to what are spoken of as *latosols*. Although these *hydrous oxide clays* will be considered later (page 106), it is well to note here that, as progress is made from a humid-temperate region to the humid tropics, the silicate clays often contain a larger and larger admixture of colloidal iron and aluminum hydrous oxides. The red and yellow soils of our southern states (page 343 are very good evidence of this transition.

Sections 4:5 to 4:7 inclusive deal with the genesis of silicate clays, the sources of their negative charges, and their chemical composition. The reader who is interested in only the more general consideration of silicate clays may choose to omit these sections and continue with section 4:8 page 95.

Table 4:2. Relative Amounts of the Three Silicate Clay Groups Present in Certain Representative Soils of the United States (Expressed as Ratios)

		Sum of Groups Taken as 100		
No. of Soils	*Soils and Areas From Which Clays Were Obtained*	*Kaolinite*	*Hydrous Micas*	*Montmorillonite*
	Southern Soils:			
5	Red podzolics, southern states [22]	90	10	0
8	Red podzolics, Ala.[23]	100	0	0
3	Black belt soils, Ala.[23]	47	0	53
	Eastern Soils:			
8	Gray podzolics, eastern U.S.[22]	63	37	0
4	Certain New York soils [24]	0	100	0
	Midwestern Soils:			
5	Iowa soils [25]	11	26	63
3	Midwestern soils [26]	25	63	12
5	Iowa soils [27]	16	3	81
	Western Soils:			
4	Desert Soils [22]	22	78	
12	Arizona soils [28]	5	52	43

4:5. GENESIS OF SILICATE CLAYS [29]

The silicate clays are developed most abundantly from such minerals as the feldspars, micas, amphiboles, pyroxines, and the like. Apparently the transformation of these minerals into silicate clays takes place in soils, and else-

[22] From data presented by Alexander, L. T., S. B. Hendricks, and R. A. Nelson, "Minerals Present in Soil Colloids; II. Estimation in Some Representative Soils," *Soil Sci.*, 48: 273–279, 1939.

[23] See Pearson, R. W., and L. E. Ensminger, "Types of Clay Minerals in Alabama Soils," *Proc. Soil Sci. Amer.*, 13: 153–156, 1948. Also see Coleman, N. T., M. L. Jackson, and A. Mehlich, "Mineral Composition of the Clay Fraction: II. of Several Coastal Plain, Piedmont and Mountain Soils of North Carolina," *Proc. Soil Sci. Soc. Amer.*, 14: 81–85, 1949.

[24] Martin, R. T., and M. B. Russell, "Clay Minerals of Four Southern New York Soils." *Soil Science*. In press, 1952.

[25] Russell, M. B., and J. L. Haddock, "The Identification of Clay Minerals in Five Iowa Soils by the Thermal Method," *Proc. Soil Sci. Soc. Amer.*, 5: 90–94, 1940.

[26] Nelson, R. A., and S. B. Hendricks, "Specific Surface of Some Clay Minerals, Soils and Soil Colloids," *Soil Sci.*, 56: 285–296, 1943.

[27] Peterson, J. B., "Relation of Parent Material and Environment to the Clay Minerals in Iowa Soils," *Soil Sci.*, 61: 465–475, 1946.

[28] Buehrer, T. F., D. O. Robinson, and J. M. Deming, "The Mineral Composition of the Colloidal Fraction of Some Southwestern Soils in Relation to Field Behavior," *Proc. Soil Sci. Soc. Amer.*, 13: 157–165, 1948.

[29] This subject is briefly summarized by Kerr, P. F., M. S. Main, and P. K. Hamilton, *Occurrence and Microscopic Examination of Reference Clay Mineral Specimens.* American Petroleum Institute project 49, Preliminary Report No. 5, pp. 1–14, 1950.

where, by at least two distinct processes: (a) a comparatively slight physical and chemical *alteration* of the primary minerals and (b) a *decomposition* of the original minerals, with the subsequent *recrystallization* of certain of their decomposition products into the silicate clays. These processes will each be given brief consideration.

Alteration. Alteration of the minerals may be encouraged by chemical attacks with the consequent removal of certain soluble constituents and the substitution of others within the crystal lattice. For example, hydrolysis results in the removal of such soluble constituents as Na^+ and K^+. This may be illustrated using the hydrolysis of microcline as a case in point.

$$KAlSi_3O_8 + HOH \longrightarrow HAlSi_3O_8 + KOH$$

This same hydrolyzing water often carries in solution certain ions which may be substituted for elements originally within the mineral framework. By changes such as these, the original minerals slowly become porous and are thereby subject to physical disintegration into the smaller clay particles. Thus, by physical and chemical alterations clays may be formed without any major change in the fundamental structure of the original minerals. Illite is a good example.

Crystallization. The crystallization of silicate clays from soluble weathering products of other minerals is perhaps even more important in clay genesis than is alteration. A good example is the formation of kaolinite from solutions containing soluble aluminum and silicon. This process of recrystallization involves a complete change from the structural make-up of the original minerals and is usually the result of much more intense weathering than that required by the alteration process described above.

Moreover, such crystallization makes possible the formation of more than one kind of clay from a given mineral. The exact silicate colloid which forms apparently depends upon the conditions of weathering.

Relative stages of weathering. The more specific conditions resulting in the formation of one or more of the three important types of clay are shown in Figure 4:5. Perhaps the first generalization to be drawn from this outline is that there is a difference in the weathering stage of the three minerals. The hydrous micas apparently represent the youngest weathering stage of the three, while kaolinite represents the oldest.[30] Montmorillonite is considered to occupy an intermediate stage of weathering. With Figure 4:5 as a guide let us consider briefly the conditions which might yield each of the three groups of clays.

Genesis of individual clays. Hydrous micas represented by illite are thought to be formed, if conditions are favorable, by the alteration of feldspars and especially of the micas. This is postulated because illite is so similar to muscovite

[30] There are, of course, stages of weathering beyond that represented by kaolinite. This mineral, for example, is subject to further decomposition with the formation of gibbsite ($Al_2O_3 \cdot 3H_2O$) which represents an even more advanced stage of weathering.

For a discussion of weathering stages see Jackson, M. L., *et al.*, "Weathering Sequence of Clay Size Minerals in Soils and Sediments I. Fundamental Generalizations," *Jour. Phys. & Coll. Chem.*, 52: 1237–1260, 1948.

in make-up and general characteristics. Apparently only a comparatively slight alteration is necessary to effect the change from one to the other. This alteration of silicate minerals to illite is characterized by the loss of much of the original sodium, calcium, magnesium and iron, while only a small fraction of the potassium is removed. At the same time considerable amounts of water become associated with the crystals—hence, the name *hydrous* micas.

In other cases, illite has apparently been formed from original minerals by recrystallization under conditions of an abundant potassium supply. In still other instances illite may be formed from montmorillonite if the latter is in contact with abundant potassium. More common, however, is the reverse reaction by which illite weathers to montmorillonite by the loss of much of its potassium. (See Fig. 4:5.)

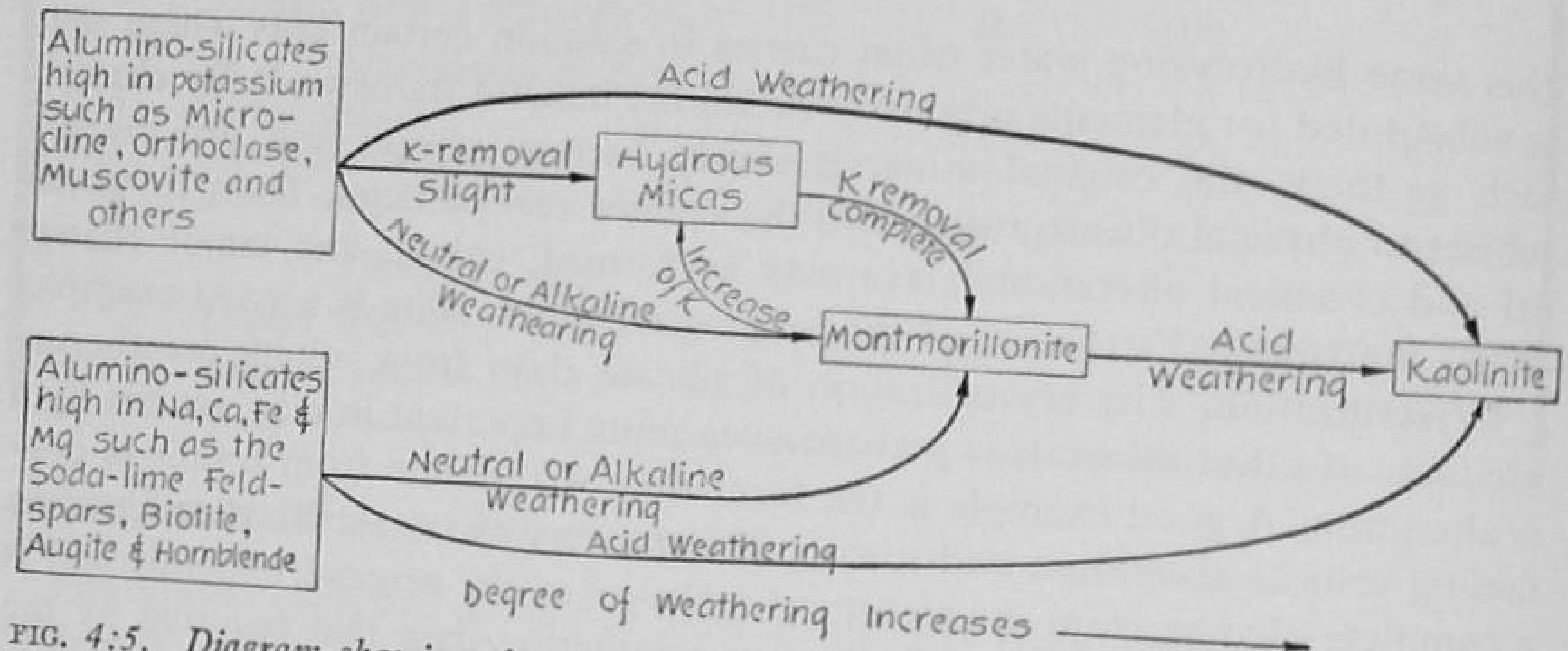

FIG. 4:5. *Diagram showing the general conditions for the formation of the three silicate clay groups and their relationship to each other. In each case, genesis is accompanied by the removal of soluble elements such as K, Na, Ca, and Mg. Also as weathering proceeds from left to right, iron and aluminum oxides are formed in addition to the above silicates. Even kaolinite is subject to decomposition, yielding gibbsite ($Al_2O_3 \cdot 3H_2O$) and soluble silica.*

When the initial weathering of rock-minerals takes place under alkaline or neutral conditions, montmorillonite is likely to be formed. (See Fig. 4:5.) Minerals containing magnesium and iron apparently weather to montmorillonite more readily than do potash silicates such as muscovite and microcline. Montmorillonite also may be formed by the removal of potassium from illite and under more acid conditions it readily gives rise to kaolinite by recrystallization.

As already stated, kaolinite represents a more advanced stage of weathering than does either of the other major types of silicate clays. It is formed from the decomposition of silicates under conditions of moderately to strongly acid weathering which results in the removal of the alkali and alkaline earth metals. The soluble aluminum and silicon products that result recrystallize, under proper conditions, to form kaolinite. This mineral, in turn, is subject to decomposition, especially in the tropics, with the formation of aluminum oxides and soluble silica.

4:6. SOURCE OF THE NEGATIVE CHARGE OF SILICATE CLAYS[31]

Exposed hydroxyl groups. There are at least two ways to account for the negative charges associated with silicate clay particles. The first method involves the hydroxyl groups which are exposed at the broken edges of most all silicate clays as well as on the flat external surfaces of minerals such as kaolinite. These hydroxyl groups are usually attached to aluminum atoms within the alumina sheet. The hydrogen of these OH-radicals dissociates slightly and the colloidal surface is left with a negative charge carried by the oxygen. The loosely held hydrogen is readily exchangeable. The situation may be represented as follows:

One O Valence is
satisfied within —O— . . . . . H^+
the crystal by Al

Negative charged crystal surface — Loosely held exchangeable hydrogen

Because of the presence of thousands of such groups, the clay particles exhibit a definite electro-negativity and are surrounded by H-ions and other cations that may have replaced such hydrogen. This phenomenon apparently accounts for most of the adsorbing capacity of 1:1 type of colloidal clays. It also is of some significance with the 2:1 types, especially at broken crystal edges.

Ionic substitution. A second reason for the over-all negative charge carried by clay crystals is the fact that substitution of one atom for another has occurred within the crystal lattice. For example, in montmorillonite magnesium atoms have substituted for some of the aluminum atoms in the alumina sheet. Furthermore, the substitution is on the basis of one Mg^{++} atom for each Al^{+++} atom replaced. Therefore, each substitution results in an unsatisfied negative valence since a three valent atom is replaced by a two valent one. This may be shown as follows if we assume that the three valences of the aluminum atoms were satisfied by an equivalent of one O atom and one OH group:

Alumina Sheet (No substitution)	Alumina Sheet (Mg substituted for Al)
$O{=}Al^{+++}OH^-$	$O{=}Mg^{++}OH^-$
No charge	One excess negative charge

[31] The presence of negative charges on clay particles can be demonstrated in a number of ways. One very simple method is to treat two samples of a clay with water suspensions of gentian violet and eosin red respectively. The particles of the former dye carry a positive charge and since they are markedly adsorbed by the clay, the latter must be negative. Conversely, the eosin particles, which are negatively charged, are only slightly adsorbed, if at all, by the clay.

Similarly in minerals such as beidellite and illite the substitution of a three valent atom such as Al for one of the four valent silicon atoms in the silica sheet has left an unsatisfied negative valence. This may be represented as follows since each Si is associated with an equivalent of 2 oxygen atoms:

Silica Sheet (No substitution)	Silica Sheet (Al substituted for Si)
$O^{=}Si^{++++}O^{=}$	$O^{=}Al^{+++}O^{=}$
No charge	One excess negative charge

With the 2:1 type of colloidal clays the substitution phenomenon just explained accounts for a major share of their adsorbing abilities. Substitution may have occurred in either or both the alumina and silica sheets. In addition to the magnesium and aluminum ions, iron in a similar way may enter the lattice of certain minerals.

4:7. THE CHEMICAL COMPOSITION OF SILICATE CLAYS

Using purified materials chemists have long been able to determine the formulae of minerals from accurate quantitative analyses. This was done with kaolinite long before its crystal structure was known. Later, not only was such work verified by means of X-ray diffraction patterns but also other clays, hitherto unknown, were thereby discovered and the classification much extended. Once the crystal form of any particular clay mineral is known and the position of the various atoms in its lattice ascertained, its ideal formula can readily be written.

Since the formulae of certain of the silicate clays will be referred to from time to time they are listed below. It must be remembered always that these formulae are ideal in the sense that they do not take into account probable atomic substitutions. Nor do they include adsorbed cations which are in reality true, though constantly changing, components of the micelle.

Kaolinite	$Al_4Si_4O_{10}(OH)_8$
Montmorillonite	$Al_4Si_8O_{20}(OH)_4$ (Mg substitutes for some of the Al)
Beidellite	Same except for the replacement of Al for some of the Si.
Illite	$KAl_2Si_4O_{10}(OH)_2$
Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$ Listed for comparison with illite.

It has already been strongly emphasized (page 51) that, of the various fractions into which soils are divided in making a mechanical analysis, the clay separate usually is richer in the mineral elements of nutrition than any

of the other textural groups. This is, of course, the reason why soils of fine texture are in general strong soils agriculturally. However, considering only the formulae of the more common clay types as listed above, one might wonder how this could be true since the only nutrient cited, in illite for instance, is potassium. The answer is simple but very important. It has already been in part suggested. Let us carry it further.

Unless the humus is previously destroyed, the colloidal matter as extracted from soils carries variable amounts of organic materials which contain nitrogen, phosphorus, and sulfur as well as certain metallic constituents. Other extraneous substances may also be present such as hydrous oxides of iron and aluminum in which plant nutrients may be present. Of importance also are the metallic substitutions that commonly occur in the lattice of the micelles of certain of the clays. Obviously, the nutrient content of the colloidal clays may be greatly augmented thereby. And lastly, and perhaps most important of all, is the presence of cations of many kinds—Ca^{++}, Mg^{++}, K^{+}, etc.—at the colloidal interfaces, held there by electro-static forces. That these adsorbed nutrients are available to plants is well known.

All this means that colloidal clay as it normally occurs in field soils is not made of merely of silicon, aluminum and oxygen but carries also a varied supply of plant nutrients[32] such as Ca, Mg, K, P, N and S as well as trace elements. Obviously the nutrient content of the silicate clays is by no means a minor feature of its physico-chemical organization.

4:8. WHY ADSORBED CA- AND H-IONS ARE SO PROMINENT

The adsorptive surface of humid-region silicate clay particles, as has already been suggested (page 83), usually are dominated by calcium and hydrogen ions. The why of this situation can now be explained. In the early stages of clay formation the solution surrounding the decomposing silicates undoubtedly is comparatively high in calcium, magnesium, potassium, and sodium, since all of these elements are readily liberated by weathering. These bases, of course, tend to render the solution alkaline or near alkaline and hydrogen ions are, for the time being, sparingly present. Calcium, under comparable conditions, is adsorbed more strongly than any of the other metallic cations commonly present in any quantity. Consequently, the adsorptive surfaces of the clay particles as they slowly develop, become definitely dominated by the ions of this metal. Thus, a calcium complex probably characterizes the early stages of clay genesis.

However, as organic matter gradually accumulates and soil processes

[32] For a verification respecting the nutrient content of the colloidal clay fraction see the data quoted in Lyon, T. L., and H. O. Buckman, *The Nature and Properties of Soils,* Fourth Ed., The Macmillan Company, New York, 1943, p. 76.

are fully initiated, carbonic and other acids are generated. Hydrogen ions, because they are so strongly adsorbed, gradually enter the cationic swarm by cation exchange, forcing part of the calcium out. In humid regions the replaced calcium is lost in drainage. Consequently, the clay gradually develops a calcium-hydrogen complex with an acidity in rough proportion to the dominance of the entering hydrogen ions.

In regions of lower rainfall the calcium and other bases do not leach from the soil and consequently hydrogen does not become dominant. In either case, however, one can visualize, in a general way at least, not only how silicate clays are generated, but why certain cations are so prominent at their colloidal interfaces.

4:9. CLAY AN ACID SALT

Clay particles, regardless of their mineralogical character, apparently have the same general organization. That is, they are made up of a complex negative radical, the micelle, and a miscellany of adsorbed cations. In a humid region, those cations of calcium and hydrogen are by far the most numerous. Consequently, a clay complex may be represented in the following simple and convenient way:

$$\begin{matrix} x\mathrm{Ca} \\ y\mathrm{H} \\ z\mathrm{B} \end{matrix} \boxed{\quad \text{Micelle} \quad}$$

The significance of the Ca and H of the formula are obvious since in a humid region these cations jointly dominate the complex. The B stands for the small amounts of other so-called basic cations Mg, K, Na, etc., that are usually present in the ionic outer layer. The x, y, and z indicate that the numbers of cations are variable.

It has already been emphasized that the micelle, in general, carries a multitude of negative charges. This characteristic allows it to function as a true acid radical. Consequently, by the adsorption of such cations as Ca^{++} or K^{+} or Mg^{++} it forms a salt-like compound similar to $CaSO_4$ or KNO_3. In the same way if H ions are adsorbed, an acid results—insoluble and stable, but nevertheless as definitely an acid as H_2SO_4 or HNO_3.

When by the proper laboratory manipulations the metallic cations are replaced entirely by H-ions, a clay acid or $\mathrm{H}\boxed{\text{Micelle}}$ results. In a like manner Ca-ions may be given dominance and a calcium salt, $\mathrm{Ca}\boxed{\text{Micelle}}$, comes into being. Two things, however, should be noted. Firstly, that sev-

eral different acids and calcium salts are possible depending upon the nature of the micelle—that is, whether we are dealing with kaolinite, montmorillonite, or some other clay. And secondly, that soil clays are very seldom wholly acids or wholly salts. They usually are complex combinations, so to speak, of the two groups. If looked at more concretely, the clays are actually mixtures of *complex acid salts.*

This concept and the simple formula method of expressing it make possible the explanation in a very simple way of certain colloidal transactions that undoubtedly are actually very complex. One of these, a reaction of tremendous importance—*cation exchange*—will be considered forthwith.

4:10. CATION EXCHANGE [33]

With the fundamental colloidal conceptions already presented as a background, cation exchange may be accounted for very simply. The tendency of carbonic acid to force such a transfer will be taken as illustrative of this intrinsic colloidal phenomenon. This exchange is perhaps one of the commonest and most important soil reaction.

A simple example. Consider, to begin with, a representative humid-region mineral surface soil, rather high in replaceable calcium, and functioning under optimum conditions of moisture and temperature. Since a considerable amount of CO_2 is evolved as the organic matter decomposes, the presence of carbonic acid in the soil solution is inevitable. The H-ions thus generated are exceedingly active and will tend to replace the exchangeable calcium of the colloidal complex. This occurs not only because of mass action effect but also because under comparable conditions ionic hydrogen is adsorbed more strongly than is the ionic calcium. The reaction may be shown graphically as follows, only one ion of the copiously adsorbed calcium for simplicity being represented as displaced.

$$\text{Ca}\ \boxed{\text{Micelle}} + 2\ \text{H}^+ \rightleftharpoons {}^{\text{H}}_{\text{H}}\boxed{\text{Micelle}} + \text{Ca}^{++}$$

The adjustment is very simple, almost instantaneous, and the interchange of calcium and hydrogen is chemically equivalent. Moreover, the micelles

[33] The term *base exchange* is often used in referring to this phenomenon. *Cation exchange,* however, is preferable because base exchange suggests that only metallic ions are involved in the interchange. This, of course, is incorrect.

at any particular time carry both Ca- and H-ions. In other words, the clay is an acid-salt. Also it is easy to see that, if the H-ion concentration were decreased for any reason or the Ca-ions are increased, say by liming, the adjustment would be to the left in response to mass action. Conversely, if the H-ions are increased or if the Ca-ions are removed by leaching, the adjustment would be to the right. The soil is so dynamic that the equalization is, of course, constantly changing, oscillating back and forth as conditions dictate.

Cation exchange under natural conditions. With these principles in mind suppose we write the reaction more completely and more in conformity with the situation commonly encountered in humid-region surface soils. We shall assume, for the sake of simplicity, that the number of Ca, H and other metallic cations (B) are in the ratio of 40, 40 and 20 per micelle respectively. The metallic cations (B) are considered monovalent in this case.

$$\begin{matrix} Ca_{40} \\ H_{40} \\ B_{20} \end{matrix} \boxed{\text{Micelle}} + 5\ H_2CO_3 \rightleftharpoons \begin{matrix} Ca_{38} \\ H_{45} \\ B_{19} \end{matrix} \boxed{\text{Micelle}} + \begin{matrix} 2\ Ca(HCO_3)_2 \\ B(HCO_3) \\ \text{subject to} \\ \text{loss in drainage} \end{matrix}$$

It is important to note that the adjustment of the reaction in this case is towards the right—that is, H-ions are entering and calcium and other bases[34] (B) are being forced out of the exchange complex into the soil solution. This is because the equilibrium of the system is prevented by the loss of carbonates and bicarbonates in drainage. Obviously, as long as this continues and the H-ion concentration is not correspondingly diminished, the adjustment will continue as pictured.

It is to be noted also that one micelle is taken to represent the whole colloidal fraction and that the loss of metallic cations (Ca and B) is just balanced by the gain in H-ions. That is, the exchange is in *chemically equivalent amounts.*

Loss of metallic elements. Not only is the above reaction a very excellent illustration of cation exchange but also it is one of the most important and far reaching transfers that occurs in humid-region surface soils. Since it will be referred to again and again, a few more words regarding it are in order. Because of this phenomenon, and the presence in most soils of rela-

[34] The term *base* will be used in this text to refer to such metallic cations as Ca, Mg, K, Na, Fe, etc. While this usage is technically incorrect and perhaps confusing to some, it is so common and convenient that it will be adhered to.

tively large amounts of adsorbed calcium, this element is mobile in larger amounts than any other soil metal and the metallic cation usually most copiously lost in drainage. The fact that magnesium, potassium, and sodium are affected in the same way, but to a lesser degree, serves to emphasize the rapidity with which cation exchange and leaching tend to deplete humid-region surface soils of active bases.

Moreover, the continual adsorption of H-ions by the colloidal micelles at the expense of the calcium and other bases increases the acidic properties of the clay. By equalization, this tends in turn to increase the H-ion concentration of the soil solution and the pH of the soil is thereby gradually lowered. Thus cation exchange accounts for the great loss of lime that most humid-region surface soils suffer each season (page 249) and at the same time indicates why such soils tend to become acid so rapidly.[35]

Influence of lime and fertilizer. Since cation exchange is an equilibrium response, the direction of the movement of any particular ion may readily be reversed. Hence, if lime is applied to an acid soil, that is, one in which the colloidal complex is definitely dominated by hydrogen, a replacement, the reverse of the one just cited, readily occurs. The active calcium ions by mass action replace the hydrogen and other cations. As a result, the clay becomes higher in exchangeable calcium and lower in adsorbed hydrogen. And as the soil solution adjusts to this altered proportion of bases and hydrogen, its pH perforce is raised and the whole physiological setup of the soil is modified.

One more illustration of ionic exchange will be offered. A soil fairly high in replaceable calcium is treated with a liberal application of potassium chloride, a common fertilizer salt. The exchange may be represented as follows if we assume that K-ions replace one H-ion and two each of the other cations associated with a given micelle. (Again B is considered as monovalent.)

$$\begin{array}{r}Ca_{40}\\H_{40}\\B_{20}\end{array}\boxed{\text{Micelle}} + 7\ KCl \rightleftharpoons \begin{array}{r}K_{7}\\Ca_{38}\\H_{39}\\B_{18}\end{array}\boxed{\text{Micelle}} + \begin{array}{r}2\ CaCl_2\\HCl\\2\ BCl\end{array}$$

The reaction is not difficult to interpret if the previous example was fully understood and if it is remembered that the interchange always is in chemically equivalent amounts. Obviously some of the added potassium

[35] This subject is so important in a practical way that it will receive detailed consideration in later chapters. See page 434.

pushes its way into the colloidal complex and forces out equivalent quantities of calcium, hydrogen, and other elements. These appear in the soil solution with calcium predominating largely because so much of it was originally present in an adsorbed condition and because it is displaced more easily than is hydrogen.

Although the potassium chloride encourages the loss of lime in drainage, field experiments indicate little tendency towards an increase in acidity. This probably is due to the fact that the calcium is replaced by another metallic cation. The entrance of the added potassium into the exchange complex is considered to be of advantage since a nutrient so held remains largely in an available condition but is less subject to leaching than are most fertilizer salts. Hence, cation exchange is an important consideration not only in respect to nutrients already present in soils but also in relation to those applied in commercial fertilizers and in other ways. It is no wonder that cation exchange, next to photosynthesis, is said to be "the most important chemical reaction in the whole domain of agriculture." [36]

4:11. CATION EXCHANGE CAPACITY [37]

It is probable that higher plants can readily make use of at least a part of the exchangeable constituents of soils. The nutritional importance of cation exchange is, therefore, undoubted. To the inquiring mind, a question immediately arises. What is the magnitude of this all-important property, or in technical terms, what is the *cation exchange capacity* of the various clays?

Method of expression. Before dealing with exchange capacity, or the relative adsorptive power of a clay for cations, the method of expressing

[36] Marshall, C. E., *Colloids in Agriculture,* Edward Arnold and Company, London, 1935, p. 79.

It should be noted that anionic fixation may take place and in some cases assumes considerable importance. This is especially true in respect to the adsorption of phosphate ions. This phase is dealt with on page 479.

[37] A number of different methods are available for the determination of the cation-exchange capacity of clay, humus, and whole soils. One of the common procedures is to displace the original adsorbed cations by treating the sample with an ammonium or barium acetate solution of a given pH. The amount of ammonium or barium ions adsorbed under these conditions is taken as a measure of exchange capacity. For methods see: Peech, Michael, *et al., Methods of Soil Analysis for Soil-Fertility Investigations,* U. S. Dept. of Agriculture circ. 757, 1947; and Schollenberger, C. J., and R. H. Simon, "Determination of Exchange Capacity and Exchangeable Bases in Soils," *Soil Sci.,* 59: 13–24, 1945.

Note also that the cation exchange capacity of a soil can be calculated in a rough way if its percentages of clay and humus are known. See note at bottom of page 110.

its magnitude must be explained. The unit employed is a *milliequivalent.* This term is defined as "one milligram of hydrogen or the amount of any other ion that will combine with or displace it." The quantity of a given exchangeable cation is usually expressed in terms of milliequivalents per 100 grams of dry substance.

Thus if a clay has a cation exchange capacity of 1 milliequivalent (1 m.e./100 gm.),[38] it is capable of adsorbing and holding 1 milligram of hydrogen or its equivalent for every 100 grams of dry substance. This, of course, is 1 milligram to 100,000 milligrams of clay or 10 parts per million. Therefore, an acre-furrow-slice of such a clay weighing 2,000,000 pounds could adsorb 20 pounds of exchangeable hydrogen or its equivalent.

It is well to note this term—*equivalent.* It indicates that other ions also may be expressed in terms of milliequivalents. For example, let us consider calcium. This element has an atomic weight of 40 compared to 1 for hydrogen. Each Ca^{++} ion has two charges and thus is equivalent to 2 H^{+} ions. Therefore, the amount of calcium required to displace 1 milligram of hydrogen is 40/2 or 20 milligrams. This, then, is the weight of 1 milliequivalent of calcium. If 100 grams of a certain clay is capable of adsorbing a total of 250 milligrams of calcium, the cation adsorption capacity is 250/20 or 12.5 m.e./100 gms. The milliequivalent method of expression is so convenient and is so commonly used that a person dealing with the literature of soil science must be familiar with it.

Cation exchange capacities of clays. As might be expected, the cation exchange capacity of the clay fraction of soils exhibits a wide range, since several clay minerals may be present in varying amounts. As to the individual clay minerals, the cation exchange capacities of montmorillonite, hydrous mica, and kaolinite are more or less in the order of 100, 30, and 8 millequivalents per 100 grams respectively.[39]

It is thus easy to see why the clay complex of southern soils when dominated by kaolinite should have a low exchange capacity, ranging perhaps between 5 and 20 milliequivalents. On the other hand, the clay mixtures functioning in the soils of the Middle West, where illite and

[38] The abbreviation m.e. will be used to express milliequivalent throughout this text. The number of milliequivalents are usually given for each 100 grams of material. Thus, the data may be given as, for example, 20 m.e./100 gms., etc.

[39] For exchange capacity data on a large number of samples see Kerr, P. F., *et al*, *Analytical Data on Reference Clay Minerals,* Amer. Pet. Inst. Project No. 49, Preliminary Report No. 7, pp. 91–124, 1950.

montmorillonite are likely to be prominent, have a much higher adsorptive capacity, ranging from 50 to possibly 100 milliequivalents depending on conditions.

The practical significance of the figures quoted above is far-reaching. Clays differ markedly in their cationic-exchange capacities. Hence, the soils carrying them also will differ widely in this all-important characteristic, not only because they possess different amounts of clay but also because the clay complexes themselves are so variable. The amount and nature of the humus also adds to the intricacy of the situation. Undoubtedly, the heterogeneity of soil clay is a fertility factor of tremendous importance.

4:12. OTHER PROPERTIES OF SILICATE CLAYS—PLASTICITY, SHRINKAGE AND COHESION, SWELLING, AND FLOCCULATION

Without a doubt, the cation exchange property of clay is outstanding. Yet, from the practical as well as the technical standpoint, certain other characteristics also assume considerable importance. Those to receive attention here are five—*plasticity, shrinkage* and *cohesion, swelling,* and *flocculation.* As might be expected, they all are surface phenomena and their intensity depends upon the amount and nature of the interfaces presented by the clay.

Plasticity. When a small amount of colloidal clay is dispersed in a much larger quantity of water, a condition designated by the colloidal chemist as a *sol* exists. When this relationship is reversed and the relatively small quantity of water is present, a viscous *emulsoid* condition results. The colloidal mass may now be called a *gel.* Field soils, because of the limited amount of water usually present, are normally in the gel condition.[40]

Many gels, especially the siliceous clays of humid regions, exhibit *plasticity,* that is, pliability and the capacity of being molded. This property is probably due to the plate-like nature of the clay particles and the lubricating yet binding influence of the adsorbed water. Thus, the particles easily slide over each other much like panes of glass with films of water between them. Usually those silicate clays with a high capacity for water of hydration exhibit the greatest plasticity. Thus, montmorillonite is more markedly plastic than kaolinite. Also the particular cation dominating the adsorptive interfaces is a factor, sodium encouraging a more viscous condition than calcium or hydrogen.

[40] Silicate clays are *reversible colloids* in the sense that they can be air dried and yet will imbibe water again freely and exhibit colloidal properties approaching their previous intensity. Some colloidal materials *set* on drying and are irreversible.

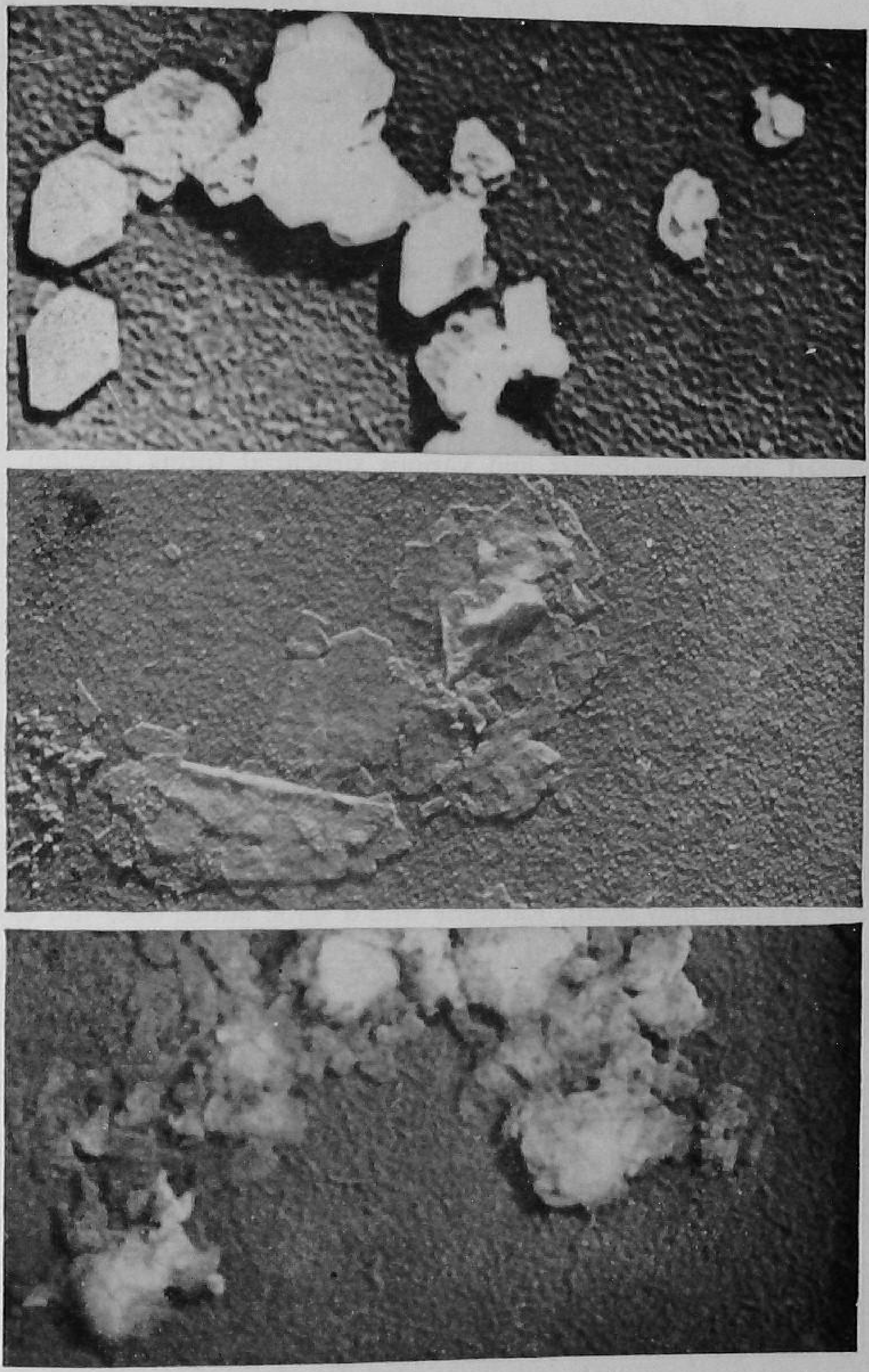

FIG. 4:6. *Crystals of kaolinite (upper), montmorillonite (center), and hydrous mica (illite), as pictured by the electron microscope. Note their crystalline nature and mica-like shape. The kaolinite crystals are characteristically 6 sided, while the others are irregular flakes. Magnification is 38,000 for both kaolinite and montmorillonite, and 45,000 for illite. (Illite and kaolinite from work of M. L. Jackson and J. A. Kittrick, University of Wisconsin; montmorillonite by B. M. Siegel, Cornell University.)*

In a practical way, plasticity is extremely important since it encourages such a ready change in soil structure. This must be considered in tillage operations. As everyone knows, the cultivation of a heavy soil when it is too wet will result in a puddled condition which is detrimental to suitable aeration and drainage. With clayey soils, especially those of the montmorillonitic type low in humus, plasticity presents a real problem. Suitable granulation therein is difficult to establish and often more difficult to maintain.

Shrinkage and cohesion. A second and third characteristic, both closely related to plasticity, are *shrinkage* and *cohesion.* As the water of a clay gel is reduced, shrinkage occurs and various structural forms develop. The shrinkage, which splits the soil mass into aggregates, is accompanied by a cohesion of the particles. This tendency of the clay particles to stick together probably is due at least in part to the mutual attraction of the clay particles for water molecules held in between them. As one might expect, montmorillonite shrinks and cracks to a much more noticeable degree than does kaolinite.

Swelling. The fourth characteristic of silicate clays to be considered, that of *swelling,* is due to the imbibition of water especially between the structural units of the micelles. (See page 88.) If the clay in question has an expanding crystal lattice (page 87) as is the case with montmorillonite, extreme swelling may occur. Kaolinite with a static lattice does not exhibit the phenomenon to any extent, while illite is intermediate in this respect. After a prolonged dry spell montmorillonitic clay soils often are crisscrossed by wide, deep cracks which at first allow rain to penetrate rapidly. But later, because of swelling, such a soil is likely to close up and become much more impervious than one dominated by kaolinite.

Apparently swelling, shrinkage, cohesion and plasticity are closely related. They are dependent, not only upon the clay mixture present in a soil and the adsorbed cation that is dominant, but also upon the nature and amount of humus that accompanies the inorganic colloids. These properties of soils are responsible to no small degree for the development of soil structure as has been previously stressed. (See page 67 and ff.)

Flocculation. Flocculation, a term applied to a coagulation of matter in the suspensoid state, is the fifth outstanding physical characteristic listed. A very good example is afforded by treating a colloidal clay suspension with a small amount of calcium hydroxide. The tiny clay particles almost immediately coalesce into floccules. Because of their combined weight,

these sink to the bottom of the containing vessel, leaving the supernatant liquid clear. The phenomenon is called *flocculation* because of the peculiar appearance of the aggregates. The same action apparently takes place in the soil itself, but, of course, much less rapidly.

Although the coagulating capacities of the several cations vary with the type of colloid under consideration, they may be ranked more or less in the order of Ca and H > Mg > K > Na. This is fortunate as the colloidal complexes of humid-region soils are usually dominated by calcium and hydrogen (page 83). Such soils gradually tend to assume a coagulated condition in the field, which is of some consequence in respect to granulation. It is well to remark again (page 69) that flocculation is not granulation, since the latter is most satisfactorily attained in the presence of organic matter. Flocculation really only sets the stage. Nor does the liming of soils particularly encourage granulation except through its influence on humus development and function.

Just why hydrogen and especially calcium ions are so effective as flocculative agents is difficult to explain.[41] It is probably related to the electrical potential of the micelles of the clay, the greater the negative charge the more stable the suspensoid and the less is its tendency to coagulate. In short, the particles repulse each other in proportion to their electrical potential. Apparently Ca- and H-ions in some way sharply reduce the effectiveness of the over-all negative charge which tends to hold the clay micelles apart. The mass attraction of the particles is then able to pull them together into clumps or floccules. The valence and hydration of the cations as well as other factors undoubtedly are also involved.

In contrast with the influence of Ca- and H-ions, adsorbed potassium and especially sodium tend to work in the opposite direction. This accounts for the dispersed and sticky condition of certain alkali soils and for the undesirable physical effects of very large annual applications of nitrate of soda to heavy soils.

It is plain that the five colloidal properties under discussion are of great importance in the practical management of arable soils. The field control of soil structure must definitely take them into account. With the colloidal viewpoint now provided, it might be worth while to review the discussion already offered (page 72 and ff.) relating to the structural management of cultivated lands.

[41] See Baver, L. D., *Soil Physics*, John Wiley and Sons, Inc., New York, 1948, pp. 93–99.

4:13. HYDROUS OXIDE CLAYS OF IRON AND ALUMINUM

The discussion so far has dealt only with silicate clays. However, hydrous oxide clays also deserve attention for at least two reasons: (1) they occur in temperate regions intermixed with silicate clays, and (2) this type of colloidal matter is often dominant in the soils of the tropics and semi-tropics. The red and yellow latosols of these regions are controlled in large degree by iron and aluminum hydrous oxides of various types.

It is difficult to say just how the water present in the make-up of these hydrous compounds is held. There are several possibilities, however, one or all of which may pertain in any particular case. Actual iron and aluminum hydroxides [$Fe(OH)_3$ and $Al(OH)_3$] may be present or water molecules of the broken bond or the planar types [42] may account for the phenomenon. All three of these methods of attachment to the oxide lattices are possible as may be the case with limonite whose formula is generally written $2Fe_2O_3 \cdot 3H_2O$. In any event, however, very small, negatively charged particles are generated carrying variable amounts of iron, aluminum, oxygen and hydrogen and possessing definite colloidal properties. These qualities, however, are not as intense as those exhibited by silicate clays, even kaolinite.

Origin of hydrous oxides. The origin of these hydrous clays is closely related to the type of climate prevalent in equatorial regions. Although tropical weathering is exceedingly drastic, its products are less acid than those of the cooler humid-temperate regions. Under tropical conditions of high temperature and rainfall and a comparatively high pH, it is postulated that the silicate minerals such as the feldspars, micas, hornblende, etc., decompose rapidly and almost completely. The silicon escapes, at least in part, in drainage as silicic acid and the iron and aluminum persist.[43] By way of illustration suppose microcline should undergo dissolution as follows:

$$KAlSi_3O_8 + HOH \longrightarrow HAlSi_3O_8 + KOH$$

$$2\ HAlSi_3O_8 + 8\ HOH \longrightarrow Al_2O_3 \cdot 3H_2O + 6\ H_2SiO_3 \text{ (Silicic acid)}$$

As silicon is removed in the form of silicic acid, the iron and aluminum, originally carried as integral parts of the original silicates and other min-

[42] See note at bottom of page 83.
[43] Byers, H. G., M. S. Anderson, and R. Bradfield, *General Chemistry of the Soil*, in Year Book of Agriculture, U. S. Dept. of Agriculture, 1938, p. 919.

erals, apparently undergo oxidation and hydration. The products, being more or less insoluble, tend to persist and accumulate as iron and aluminum gels. These impart the reddish and yellowish colors so characteristic of certain tropical soils. The origin of these hydrous clays is considered further on page 106 in connection with soil genesis.

Properties of the colloidal micelle. An understanding of silicate colloids makes it possible to deal with the organization and general characteristics of the hydrous oxide clays briefly but clearly. In the first place, their general organization is the same as those of the silicate type—that is, very small insoluble micelles, negatively charged and accompanied by a swarm of cations of which hydrogen and calcium are predominant. Hence the same generalized formula already specified

$$\begin{matrix} x\text{Ca} \\ y\text{H} \\ z\text{B} \end{matrix}\ \boxed{\text{Micelle}}$$

may be used. In so doing, however, it must always be remembered that several different types of these clays will be encountered in the field, depending on climate, parent material, drainage, and other factors.

Hydrous oxides are much lower in plasticity and cohesion than silicate clays, especially those of the montmorillonitic type. They seem also to possess a natural and more stable type of aggregation. As a consequence, soils dominated by them often can be cultivated almost immediately after a heavy rain. Moreover, they do not erode seriously unless the slope is quite steep. Structural condition is not a serious problem in most soils (latosols) controlled by them.

The cation exchange capacity of hydrous oxide clays is exceptionally low, being somewhat less than that of the kaolinitic group. This has a fertility bearing of no mean importance. Another fertility relationship is the large amount of active iron and aluminum present. These cations tend to render phosphorus, both native and added, notably unavailable to plants (page 477 and ff.), a feature not to be lightly regarded.

All the characteristics mentioned above are but a reflection of the nature of the colloidal micelles. They serve to emphasize the physical and chemical differences that can be expected when a change is made from soils dominated by a silicate complex to those where hydrous oxides prevail. A further consideration of latosols [44] will be found on page 346 and ff.

[44] It is well to remark that varying amounts of kaolinite usually will be found intermixed with the hydrous oxides. This is to be expected since kaolinite is the type

4:14. ORGANIC SOIL COLLOIDS—HUMUS

Since the clays of surface soils usually carry an appreciable admixture of humus, a brief word is necessary at this point regarding organic colloids. Otherwise the soil significance of the colloidal state of matter cannot be fully visualized.

We shall not concern ourselves here with the origin of humus or with its chemical composition. Those phases are more appropriately considered under soil organic matter. (See page 158.) Moreover, we shall merely mention in passing the color relations, the low plasticity, the low cohesion, and the high water capacity of the organic colloids. This will allow the emphasis for the present to be placed on two closely related phases: (1) the colloidal organization of the humic complex and (2) its cation exchange capacity.

The colloidal organization. The organization of the soil humus, in spite of its variable and complex chemical nature, can be simply expressed. The same general formula

$$\begin{matrix} x\mathrm{Ca} \\ y\mathrm{H} \\ z\mathrm{B} \end{matrix} \boxed{\quad \text{Micelle} \quad}$$

already employed for the clays, can be used to show the colloidal setup of humus. And if the ideas implied by the formula are clear, further explanation may be brief.

Apparently we are dealing with very fine particles or micelles, this time amorphous and organic. Again a tremendous expanse of negatively charged surface adsorbs a copious quantity of cations. In a given soil the relative proportion of these cations is about the same as that adsorbed by the clay with which the humus is so commonly mixed. And, as one would naturally expect, the cation exchange reactions, already written for clays, hold just as definitely for humus.

In short, the surface phenomenon common to the clays characterize, more or less intensely, the soil humus. Since the soil colloidal matter is a mixture of clay and humus, the possibility of expressing this heterogeneous complex by means of one simple formula is indeed fortunate. It will greatly expedite the clarification of certain ideas.

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of silicate clay that results when weathering is particularly drastic. See Coleman, R., and M. L. Jackson, "Mineral Composition of the Clay Fraction of Several Coastal Plain Soils of Southeastern United States," *Proc. Soil Sci. Soc. Amer.*, 10: 381–391, 1945.

Cation exchange capacity. In respect to cation adsorptive capacity, the contrast of humus with clay, whatever its type, is striking. It has already been suggested that the colloidal silicate minerals vary in respect to their cation exchange capacity from 8 to 10 to perhaps 100, or even 120, milliequivalents per 100 grams of dry soil. On the other hand, the capacity of well-developed humus found in mineral soils may range from perhaps 150 to 300 milliequivalents per 100 grams.

In general, 1 per cent of well humified organic matter in a mineral soil means an exchange capacity in the neighborhood of *2 milliequivalents* for every 100 grams of soil. One per cent of silicate clay, in contrast, will affect the cation exchange capacity much less, perhaps only from 0.1 to 1.0 milliequivalent, depending, of course, upon the type of clay mixture under consideration. Perhaps 0.5 of a milliequivalent would be a reasonable average figure. Although the data quoted are extremely tentative and should be used with caution, the ideas that they convey are definite and exceedingly significant.

4:15. COLLOIDAL CONSIDERATIONS OF THE WHOLE SOIL

We have now run the gamut of substances that commonly make up the colloidal complex of mineral soils—kaolinite, illite, montmorillonite, hydrous oxides of iron and aluminum, and humified organic matter. Moreover, their constitution, organization, and major characteristics are, in general, familiar. Let us now see how these various features are reflected in representative mineral soils.

Two ideas of a general nature stand out clearly from the preceding discussion: (1) the colloidal situation within a normal soil is infinitely complicated and (2) practically every soil characteristic and activity has, in one way or another, a colloidal phase.

The first idea needs little added emphasis. Soils are a mixture of noncolloidal and colloidal materials in all possible proportions. Both types are complicated, especially the latter. The colloidal fraction,[45] made up as it is

[45] One method for determining the amount of colloidal matter in soil involves a comparison of the relative water absorbing capacities of the whole soil and the colloidal separates contained in that soil. The relationship is as follows:

$$\frac{\text{Adsorption per gram of whole soil}}{\text{Adsorption per gram of extracted colloid}} \times \frac{100}{1} = \text{\% of colloidal matter in soil sample.}$$

See Gile, P. L., *et al.*, *Estimation of Colloidal Material in Soils by Adsorption*, Bulletin 1193, U. S. Dept. of Agriculture, 1924.

A hydrometer method of estimating the amount of colloidal matter in soils has been

of a heterogeneous mixture of several different clays and humic bodies of variable composition, presents a situation with which, until recent years, scientists were unable to cope. Its secrets are now yielding to persistent research.

As to the second general idea, any chapter of this text offers ample illustration and confirmation. Since colloidal relationships are so numerous and varied, only two phases, particularly applicable at this point, will be considered—*cation-exchange capacity* and *percentage base saturation* of whole soils.

4:16. THE CATION EXCHANGE CAPACITY (C.E.C.) OF WHOLE SOILS[46]

Since the phenomenon of cation-exchange is so important in soils, the question of the magnitude and variability of their total exchange capacity is sure to arise. This may be met by considering data regarding a wide variety of surface soils. These are presented in Table 4:3.

Variability of the C.E.C. of soils. In scanning the data of Table 4:3 one perhaps notices first of all the great range in the figures presented, the highest approaching 60 milliequivalents per 100 grams. This is to be expected since soils vary so tremendously in humus content and in the amounts and kinds of clay present. It is one thing to have kaolinite as the major clay and quite another if montmorillonite is in the ascendency, so different are their individual capacities to adsorb cations. As already suggested, the latter commonly exceeds the former perhaps eight to ten fold (page 101). Moreover, humic residues developed under different climates or from diverse plant tissues do not always possess the same adsorptive power. All of these factors contribute very definitely to the exceptional variability and wide range in the data presented.

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devised by Bouyoucos. See Bouyoucos, G. J., "The Hydrometer as a New and Rapid Method of Determining the Colloidal Content of Soils," *Soil Sci.*, 23: 319–330, 1927. Also, "A Sensitive Hydrometer for Determining Small Amounts of Clay or Colloids in Soils," *Soil Sci.*, 44: 245–246, 1937.

[46] In the preceding section the average figures for the cation exchange capacity of representative silicate clay (.5 m.e. for each per cent) and for well humified organic matter (2.0 m.e. for each per cent) were quoted. Using these figures it obviously is possible to calculate in a rough way the cation exchange capacity of a humid-temperature region surface soil from the percentages of clay and organic matter present.

For instance, suppose that the soil in question carries 16 per cent of silicate clay and 4 per cent of well humified organic matter. The exchange capacity (per 100 gms. soil) due to the clay would be 8 m.e. (.5 × 16) and that of the organic matter also 8 m.e. (2 × 4). The total exchange capacity of the whole soil would, therefore, be in the neighborhood of 16 m.e. per 100 gms.

Table 4:3. Cation Exchange Capacity of a Wide Variety of Surface Soils from Various Parts of the United States[47] (in Milliequivalents per 100 Gms. of Dry Soil)

Soil Type	*Exch. Cap. m.e./100 gm.*	*Soil Type*	*Exch. Cap. m.e./100 gm.*
Sands:		*Silt Loams:*	
Sassafras (N.J.)	2.0	Delta (Miss.)	9.4
Plainfield (Wis.)	3.5	Fayette (Minn.)	12.6
		Spencer (Wis.)	14.0
Sandy loams:		Dawes (Nebr.)	18.4
Greenville (Ala.)	2.3	Carrington (Minn.)	18.4
Sassafras (N.J.)	2.7	Penn (N.J.)	19.8
Norfolk (Ala.)	3.0	Miami (Wis.)	23.2
Cecil (S.C.)	5.5	Grundy (Ill.)	26.3
Coltneck (N.J.)	9.9		
Colma (Calif.)	17.1	*Clays & Clay loams:*	
		Cecil clay loam (Ala.)	4.0
Loams:		Cecil clay (Ala.)	4.8
Sassafras (N.J.)	7.5	Coyuco sandy clay (Calif.)	20.2
Hoosic (N.J.)	11.4	Gleason clay loam (Calif.)	31.5
Dover (N.J.)	14.0	Susquehanna clay (Ala.)	34.2
Collington (N.J.)	15.9	Sweeney clay (Calif.)	57.5

Relation of C.E.C. to texture and organic matter. A more careful examination of the table will reveal that a rough correlation exists between texture and exchange capacity, the latter in general increasing as soils become heavier. This is readily explained, since sands and sandy loams are low in colloidal clay and are very likely to be deficient in humus also. Heavier soils in marked contrast always carry more clay and generally more organic matter as well. Hence their cation adsorption capacities are usually higher.

While variations in exchange capacity are expected to be rather pronounced between soils of different textures, it is perhaps a little surprising

[47] These data were compiled from the following publications:

Pierre, W. H., and G. C. Scarseth, "Determination of Percentage Base Saturation of Soils and Its Value in Different Soils at Definite pH Values," *Soil Sci.*, 31: 99–114, 1931.

Rost, C. O., and C. A. Rowles, "A Study of the Factors Affecting the Stability of Soil Aggregates," *Proc. Soil Sci. Soc. Amer.*, 5: 421–433, 1940.

Bear, Firman E., A. L. Prince, and J. L. Malcolm, "The Potassium-Supplying Power of 20 New Jersey Soils," *Soil Sci.*, 58: 139–149, 1944.

Barshad, Isaac, "A Pedologic Study of California Prairie Soils," *Soil Sci.*, 61: 423–442, 1946.

Larson, W. E., *et al.*, "Characteristics of Three Soils from the Chernozem and Chestnut Soil Regions of Nebraska," *Proc. Soil Sci. Soc. Amer.*, 12: 420–423, 1947.

Rendig, V. V., "Rapid Determination of Base Exchange Capacity of Soils with Flame Photometer," *Proc. Soil Sci. Soc. Amer.*, 12: 449–451, 1947.

to find that the differences within textural groups are at times just as striking. In some instances organic matter differences seem to account for the deviations. This may be the case with the silt loams of Minnesota, Wisconsin, and Nebraska and the clay soils of California cited in Table 4:3. But when the Cecil clay and clay loam of Alabama are compared with the Susquehanna clay of the same state some other factor must be operative since all of these soils are rather low in organic matter. That the other factor might well be the type of clay present in each case is evidenced by the following tentative calculation.

Influence of type of colloid. It is well known that the clay fraction of the Cecil soil is dominated by kaolinite which when pure has a cation adsorption capacity of about 8 m.e./100 gm. Consequently, even if its clay content in toto should be 30 per cent, the Cecil soil probably would not possess a cation exchange capacity due to the clay of much over 2 or 3 milliequivalents. The low figure of Table 4:3 is thus readily accounted for.

On the other hand, the inorganic colloidal mixture of the Susquehanna clay is dominantly montmorillonitic in nature. Assuming in this case that the exchange capacity of its clay complex is approximately 90 m.e./100 gm. and that the soil contained 30 per cent of this clay, its adsorptive power would be in the neighborhood of 27 m.e./100 gm. This is not taking into consideration the adsorptive capacity of humus that might be present. Thus the type of clay present probably accounts for the figure quoted for the Susquehanna soil.[48]

These findings afford an opportunity again to voice a word of caution in respect to a previous generalization. It is suggested (page 89) that the soils of our southern states are to a considerable degree dominated by kaolinitic clays (1 to 1 lattice), while Northern soils often are characterized by clays of the 2 to 1 lattice type. That such a generalization should be

[48] That the calculations above are by no means overdrawn is shown by the investigation of the cation adsorption capacity of two North Carolina soils—one a Cecil clay, which is definitely kaolinitic, and the other a White Store clay, dominated by montmorillonite. The samples were taken from the subsoil, thus obviating differences in organic matter and making it possible to ascribe differences in exchange capacity definitely to the kind and amount of the respective clay complexes carried by the two soils.

The exchange capacity figures reported were 9.7 and 25.9 milliequivalents respectively, showing a difference of such an order as to validate the conclusions drawn from foregoing illustrative calculations. See Mehlich, Adolf, "Effect of Type of Soil Colloid on Cation-Adsorption Capacity and on Exchangeable Hydrogen and Calcium as Measured by Different Methods," *Soil Sci.*, 60: 289–304, 1945.

applied with caution is evidenced by the case of the two southern soils discussed in the preceding paragraph—one kaolinitic and the other montmorillonitic. Such situations are found not only in the same state but in sites that are only a very few miles apart. Obviously then, the type of clay mixture that may characterize a soil is not necessarily determined entirely by climate. Parent material, time of weathering, drainage and other factors participate in complicated interplay. It is not surprising, therefore, that montmorillonitic clay mixtures are found in southern climes, and that both kaolinite and illite characterize certain northern soils.

4:17. THE PERCENTAGE BASE SATURATION OF SOILS

Let us carry the consideration of the colloidal nature of soils one step farther and inquire briefly as to the relative amounts of exchangeable bases (that is, Ca, Mg, K, etc.) and exchangeable hydrogen ions that are carried by the colloidal complexes of various soils. This relationship ordinarily is shown by the *percentage base saturation*. It is the percentage extent to which the colloidal complex is occupied by exchangeable bases. Thus, if the percentage base saturation is 80, four-fifths of the exchange capacity is satisfied by bases and only one-fifth by hydrogen ions. The example in Figure 4:7 should be helpful in showing this relationship.

Per cent base saturation and pH. The percentage base-saturation data for different soils show wide variations. For example, the colloidal complexes in arid-region soils are practically saturated with bases. On the other hand, those of humid-region soils, due to ionic exchange and leaching, are likely to be comparatively low in metallic cations and correspondingly higher in adsorbed hydrogen. Such differences are extremely important not only from the fertility standpoint but also in respect to the H-ion concentration of the soil solution.

In regard to this last suggestion, it is sufficient at present to say that a rather definite correlation exists between the percentage base-saturation of a soil and its pH. As the former is reduced, due to the loss in drainage of lime and other metallic constituents, the pH also is lowered in a more or less definite proportion.[49] This is in line with the common knowledge that leaching tends ordinarily to increase the acidity of humid-region soils. The

[49] Within the range of pH 5 to 6 the ratio for humid-temperate region mineral soils is roughly a 5 per cent base saturation change for every .10 change in pH. Thus, if the percentage base saturation is 50 per cent at pH 5.5, it should be 25 and 75 per cent at pH 5.0 and 6.0 respectively. This relationship is worth remembering.

mechanism by which colloids exert a control on soil pH will be considered later. (See page 391.)

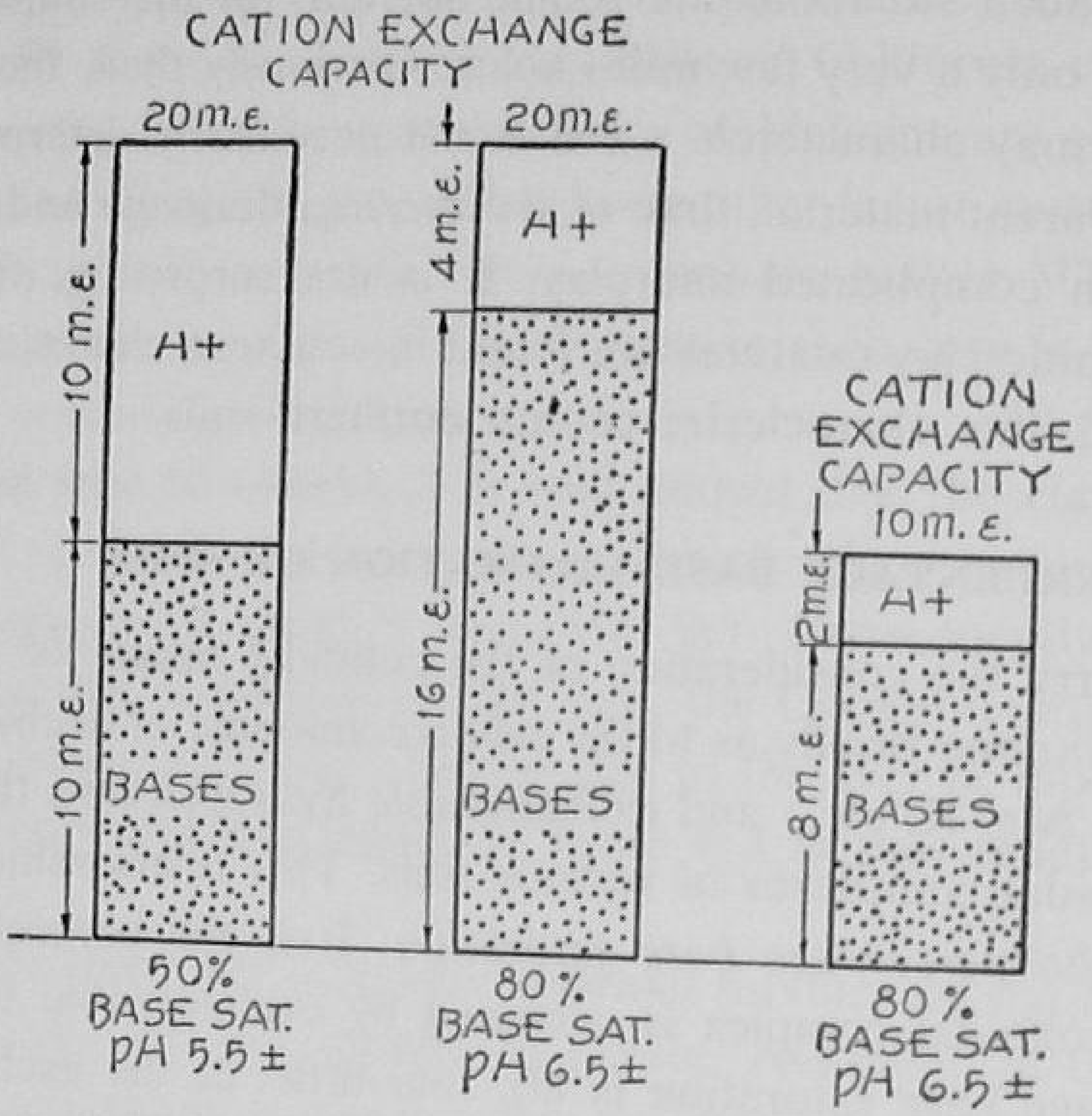

FIG. 4:7. *Diagrams explanatory of percentage base saturation. Three soils are pictured with percentage base saturations of 50, 80, and 80 respectively. The first is a clay loam; the second, the same soil satisfactorily limed; and the third, a sandy loam with a cation exchange capacity of only 10 m.e.*

Note especially that soil pH is correlated more or less closely with percentage base saturation. Also note that the sandy loam (right) has a higher pH than the acid clay loam (left) even though the latter contains more exchangeable bases.

Humid region soils. With the differences in cation exchange capacity and base-saturation of soils clearly in mind, the concept may be more or less completed by suggesting certain pertinent data of an average nature. A representative surface mineral soil from a humid-temperate region and at an intermediate fertility level, will be considered. The data (Table 4:4) are merely tentative but it is felt that they afford a more tangible idea of cationic adsorption and other related characteristics than has as yet been offered. The notes as well as the table itself merit diligent study.

Arid region soils. The cationic exchange situation in an arid-region surface soil is just as easily pictured. The adsorbed hydrogen is lower and

Table 4:4. Suggested Cation Exchange Data for a Representative Mineral Surface Soil of a Humid Temperate Region

Exchangeable calcium—(Ca)[50]	6 to 9 m.e.[51]
Other exchangeable bases (B)	2 to 3 m.e.
Exchangeable hydrogen (H)	4 to 6 m.e.
Cation exchange capacity	12 to 18 m.e.
Percentage base saturation	66.6
Probable pH	5.6 to 5.8

the metallic cations are higher giving a percentage base saturation of 90 or even 100. The pH, of course, is around 7 or may exceed this figure if carbonates, especially those of sodium, are present. These changes definitely indicate the differences that in general can be expected when representative humid and arid temperate-region soils are compared in respect to their cation exchange characteristics, percentage base saturation, and the pH of their solutions. By way of illustration tentative exchange data for a representative chernozem surface soil, characteristic of certain semi-arid temperate regions, are offered in Table 4:5.

4:18. CATION EXCHANGE AND THE AVAILABILITY OF NUTRIENTS

It is generally assumed that adsorbed nutrients are rather readily available both to higher plants and to microorganisms. Experimental results

[50] Note that the generalized formula— $\begin{matrix} x\mathrm{Ca} \\ y\mathrm{H} \\ z\mathrm{B} \end{matrix} \boxed{\text{Micelle}}$ —is being evaluated.

[51] In order that the amounts of such exchangeable cations as Ca, Mg, K, etc. may be accurately compared with the amounts of adsorbed H, they must be expressed in milliequivalents. The conversion is easy but follow it through until you are familiar with every step. Its mastery is essential.

Suppose, for example, that 40 mgs. of exchangeable Ca are present in 100 gms. of dry soil. Since one atom of Ca (atomic wt. 40) will replace two atoms of H (atomic wt. 1), the weight relation is 40:2 or 20:1. Hence, the 40 mgs. of Ca is equivalent to 2 mgs. of H or to 2 milliequivalents.

One milliequivalent of any cation per 100 grams of soil is equivalent on the basis of the acre-furrow-slice (2,000,000 lbs. of dry soil) to 20 lbs. of hydrogen (page 101) or to 1000 lbs. of $CaCO_3$. This is a convenient conversion relation to remember. But be sure that you can prove it.

Applying this conversion to the maximum figures quoted in Table 4:4, we find that the total exchange capacity of the soil in question is equivalent to 18,000 lbs. of $CaCO_3$ per acre-furrow-slice and that the actual amount of exchangeable calcium present is equal to 4½ tons of $CaCO_3$. These figures provide a definite idea as to the magnitude of the exchange capacity of soils and as to the amount of replaceable calcium that might be present.

Table 4:5. Suggested Cation Exchange Data for a Representative Chernozem Surface soil.

Exchangeable calcium—(Ca)	13 to 16 m.e.
Other exchangeable bases (B)	6 to 8 m.e.
Exchangeable hydrogen (H)	1 to 2 m.e.
Cation exchange capacity	20 to 26 m.e.
Percentage base saturation	95 and 92
Probable pH	7±

unquestionably bear this out. But just how is the transfer from soil colloid to soil organisms effected? We have in cation exchange a mechanism that undoubtedly facilitates the availability of nutrients held in this way.

Nutrient absorption. Apparently cation exchange functions in two ways as nutrients are released for the use of plants and microorganisms. In one case the nutrients freed by cation exchange find their way into the outer and freer portion of the soil solution. There they may ultimately contact the absorptive surfaces of root hairs and microorganisms or they may be removed in drainage water. The large amounts of calcium, magnesium, and potassium lost by leaching indicate that many cations escape biological absorption.

Secondly, if the contacts of the root hairs and microorganisms with the soil colloidal surfaces are close enough, there may be a direct exchange of cations between the soil and the roots or microbes. (See Fig. 2:6.) Under such a condition the H-ions, generated at the surfaces of both the root hairs and the microorganisms, are thought to effect a direct interchange with the adsorbed nutrient cations of the soil without any of these ions having first been released to the soil solution. This contact absorption has been mentioned before (page 43) and undoubtedly is of much importance. It enables plants to easily acquire nutrients that might later escape in drainage or even might not overwise be available.

Cation saturation and nutrient absorption by plants. The availability of adsorbed nutrients is not always so easy as the explanation above might lead one to surmise. This is because several factors operate to expedite or retard the release of nutrients to plants. Firstly, there is the proportion of the cation exchange capacity of the soil occupied by the nutrient cation in question. For instance, if the percentage calcium saturation of a soil is high, the displacement of this cation is comparatively easy and rapid. In the same way, other cations, such as magnesium and potassium, must occupy

a certain proportion of the total exchange capacity before they are easily dislodged.

The availability of an adsorbed cation, therefore, is not entirely a question of the number of milliequivalents present. For instance, 6 milliequivalents of exchangeable calcium in a soil whose exchange capacity is 8 probably would mean ready availability. But 6 milliequivalents when the total exchange capacity of a soil is 30 present quite the opposite condition. This is one reason why when liming for a crop that requires abundant calcium, such as alfalfa, the base saturation of at least part of the soil should approach or even exceed 90 per cent.

Influence of associated ions. A second important factor influencing the ease of the ionic exchange of a given cation is the effects of the ions held in association with it. For instance, assume that a suitable amount of exchangeable calcium is held by a soil. Also postulate that in one case its major associative cation is hydrogen and in a second case the accompanying ion is dominantly sodium. Each associated cation is present in amounts chemically equivalent to the adsorbed calcium. Since exchange resistance is in general of the order: H > Ca and Mg > K and Na, it is obvious that in the first case postulated, Ca-ions will be present in the soil solution in quantity because they are held less tenaciously than the associated H-ions. In the second case the concentration of the Ca-ions in the soil solution will be relatively low until the replaceable Na-ions have been much reduced.

The effect of type of colloid. Thirdly, the several types of colloidal micelles differ in the tenacity with which they hold specific cations. This, undoubtedly, will affect the ease of cation exchange. For instance, the tenacity with which Ca is held by montmorillonite is much greater than that of kaolinite. As a result it is suggested [52] that a montmorillonitic clay must be limed to at least 70 per cent base saturation before calcium will exhibit an ease and rapidity of exchange that will satisfy growing plants. A kaolinitic clay, on the other hand, seems to liberate calcium much more readily, serving as a satisfactory source of this constituent at a much lower percentage base-saturation. Obviously the liming programs of the two soils will be somewhat different, due in part to the factor under discussion.

The influence of the replacing cation. Fourthly, there is the particular

[52] See Mehlich, A., and W. E. Colwell, "Influence of Nature of Soil Colloids and Degree of Base Saturation on Growth and Nutrient Uptake by Cotton and Soybeans," *Proc. Soil Sci. Soc. Amer.*, 8: 179–184, 1944. Also see Chu, T. S., and L. M. Turk, *Growth and Nutrition of Plants as Affected by Degree of Base Saturation of Different Types of Clay Minerals,* Mich. Agr. Exp. Sta., Tech. Bul. 214, June, 1949.

cation effecting the exchange and its mass-action influence upon the rate of replacement. Under comparable conditions the order of replacing capacity is, in general, H > Ca and Mg > K and Na. In humid regions where leaching is prevalent, H-ions of course readily enter the adsorptive complex of soils, and bases, especially Ca-ions, are more or less easily forced out. The greater the concentration of H-ions the more ready is this exchange.

Suppose, however, that potassium chloride is added as a fertilizer and K-ions, chemically equivalent to the H-ions postulated above, are momentarily brought to bear on the adsorbed Ca-ions. That the amount of calcium forced out will be less than that effected by the hydrogen is a foregone conclusion. And being low in replacing capacity, the potassium must, unlike the hydrogen, depend entirely on mass action. Obviously, then, the particular cations pitted against each other are factors in cation exchange equilibria.

4:19. CONCLUSION

No attempt will be made to summarize this chapter except to reemphasize three things: (1) the unique physical and chemical organization of soil colloids, (2) their capacity to expedite certain phenomena vital to plant and animal life and (3) the bearing of these phenomena on soil management and crop production.

Yet an understanding of these phases, even in detail, leaves the picture incomplete. The concept must be bio-colloidal. Therefore, let us carry our knowledge of the colloidal state of matter with us as we consider soil organisms, soil organic matter, and the genesis of humus.

CHAPTER

5

The Organisms of the Soil[1]

IN THE PRECEDING consideration of the soil colloidal matter the major emphasis was placed on the inorganic fractions—the clays. It is at once evident, however, that the colloidal concept will remain incomplete unless at least an equal attention is accorded the organic portion of this all important state of matter. The soil organic fractions, especially the humus, await further examination.

First, however, another phase, most intimately related claims our attention. Humus, like clay, is a product of dissolution and synthesis. And the agency responsible is the organic population of the soil. Before a proper understanding of the various organic transformations and products can be acquired, some attention must be accorded the fauna and flora, the living colloidal fraction, of the soil. In this study it is well to note at the outset that the major stress will be placed, not on classification, but upon the biochemical changes induced by the various organisms. Consequently, the grouping employed (Table 5:1) is very broad and simple.

A vast number of organisms live in the soil. By far the greater proportion of these belong to plant life. Yet animals are not to be minimized, especially in regard to the early stages of organic decomposition. Most soil organisms, both plant and animal, are so minute as to be seen only by the aid of the microscope. The number ranging from this size to that

[1] One of the better comprehensive treatises on the subject of soil organisms is Waksman, Selman A., *Principles of Soil Microbiology*, The Williams and Wilkins Company, Baltimore, 1932. A more popular consideration by Waksman, Selman A., and Robert L. Starkey, is *The Soil and the Microbe*, John Wiley and Sons, Inc., New York, 1931. See also, Russell, E. John, and E. W. Russell, *Soil Conditions and Plant Growth*, Longmans, Green and Company, New York, 1950; and Lutz, H. J., and R. F. Chandler, Jr., *Forest Soils*, John Wiley and Sons, Inc., New York, 1946.

of the larger rodents is comparatively small. For convenience the animals will be considered first. (See Table 5:1.)

Table 5:1. Chart Showing the More Important Groups of Organisms That Commonly Are Present in Soils. The Grouping Is Very Broad and General as the Emphasis Is To Be Placed, Not on Classification, but Upon Bio-chemical Activity.

Animals	Macro	Subsisting largely on plant materials	Small mammals—squirrels, gophers, woodchucks, mice, shrew	
			Insects—springtails, ants, beetles, grubs, etc.	
			Millipedes	
			Sowbugs (woodlice)	
			Mites	
			Slugs and snails	
			Earthworms	
		Largely predatory	Moles	
			Insects—many ants, beetles, etc.	
			Mites, in some cases	
			Centipedes	
			Spiders	
	Micro	Predatory or parasitic or subsisting on plant residues	Nematodes	
			Protozoa	
			Rotifers	
Plants	Roots of higher plants			
	Algae	Green		
		Blue-green		
		Diatoms		
	Fungi	Mushroom fungi		
		Yeasts		
		Molds		
	Actinomyces of many kinds			
	Bacteria	Aerobic	and	Autotrophic
		Anaerobic		Heterotrophic

5:1. SOIL MACROANIMALS [2]

The larger animals of the soil are chiefly (1) rodents and insectivora, (2) insects, (3) millipedes, (4) sowbugs (woodlice), (5) mites, (6) slugs and snails, (7) centipedes, (8) spiders, and (9) earthworms.

[2] For data concerning the animal life of the forest soils of northeastern United States, see Eaton, Theodore H., Jr., and Robert F. Chandler, Jr., *The Fauna of Forest Humus Layers,* Memoir 247, Cornell Univ. Agr. Exp. Sta., 1942; and Hamilton, W. J., Jr., and D. V. Cook, "Small Mammals and the Forest," *Jour. of Forestry,* 38: 468–473, 1940.

The rodents are represented by the ground squirrel, pocket gopher, woodchuck, kangaroo rat, and prairie dog, depending upon the particular region under consideration. The activity of these animals results in the pulverization, granulation, and transfer of very considerable quantities of soil. Insect-eating animals, especially moles, are equally important in many cases. While the activities of these various animals are usually unfavorable to agricultural operations, the effect on the soil is often beneficial and analogous to that of tillage. Not only do these animals incorporate much organic matter in soils but also their burrows serve to aerate and drain the land. In some cases they so thoroughly disturb the various soil horizons as to make the original nature of soil profiles difficult to ascertain.

A great variety of insects is found in soils. Some of them have very little influence on the organic matter, while others, such as ants, beetles, springtails, etc., appreciably affect the humic constituents, either by translocation or by digestion. In some regions, the work of ants is often especially noticeable. In association with these insects are millipedes, sowbugs, mites, slugs, and snails, organisms that use more or less undecomposed plant tissue as food. They thus serve to initiate the decomposition processes that are continued by bacteria and fungi. (See Fig. 5:1.)

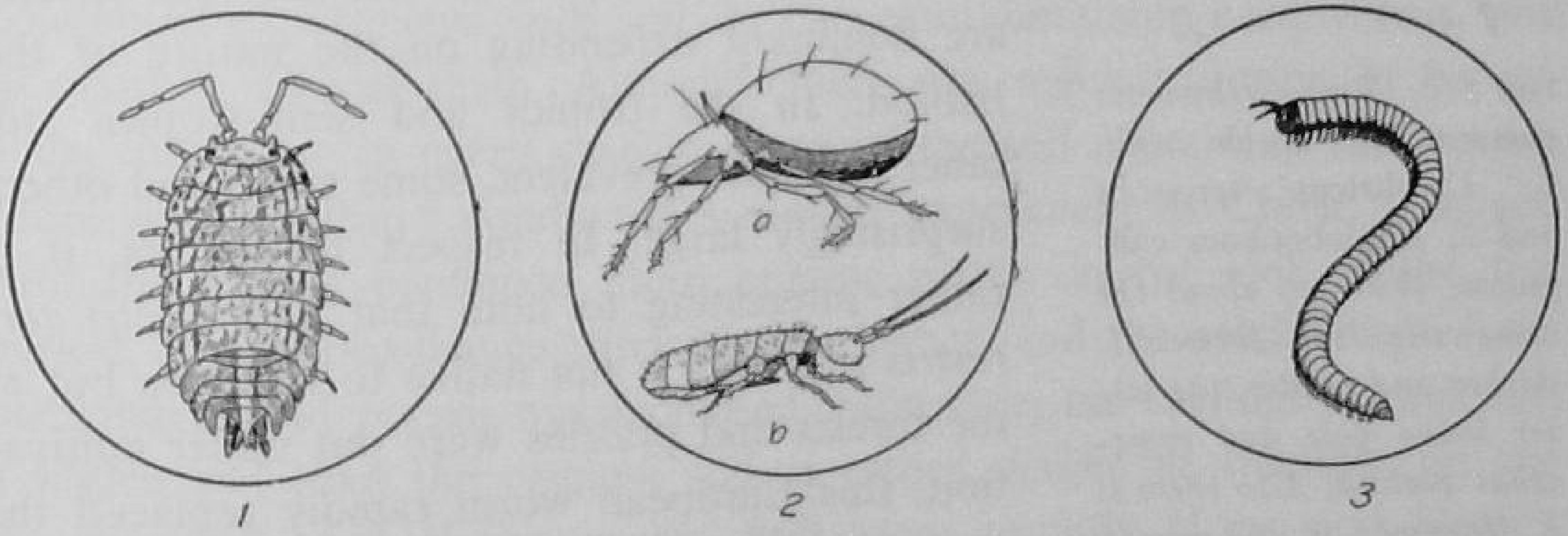

FIG. 5:1. *Four animals having much to do with the digestion of the organic matter especially of forest soils. 1, Sow-bug* (Trachelifus rathkei); *2a, mite* (Oribata Sp.); *2b, Spring-tail* (Tomocerus Sp.); *3, millipede* (Parajulus Sp.).

In peat soils, the millipedes often not only have much to do with the digestion of the organic matter but markedly influence, by forming casts, the structure of the horizons in which they are active. Centipedes and spiders, being in large degree predatory, are of minor importance, both in mineral and peat soils, as far as the processes of humus synthesis are concerned.

Many of the animals just mentioned are rather unimportant in organic transfers as individual groups. In mass, however, they become highly significant even if they do nothing more than contribute at death to the accumulation of decomposable tissue. A number of these organisms are of more concern as plant or animal pests. Thus they are of greater interest to the pathologist and especially the entomologist than to the student of soil science. In any case, however, they are a part of perhaps the most intricate biological cycle in the world.

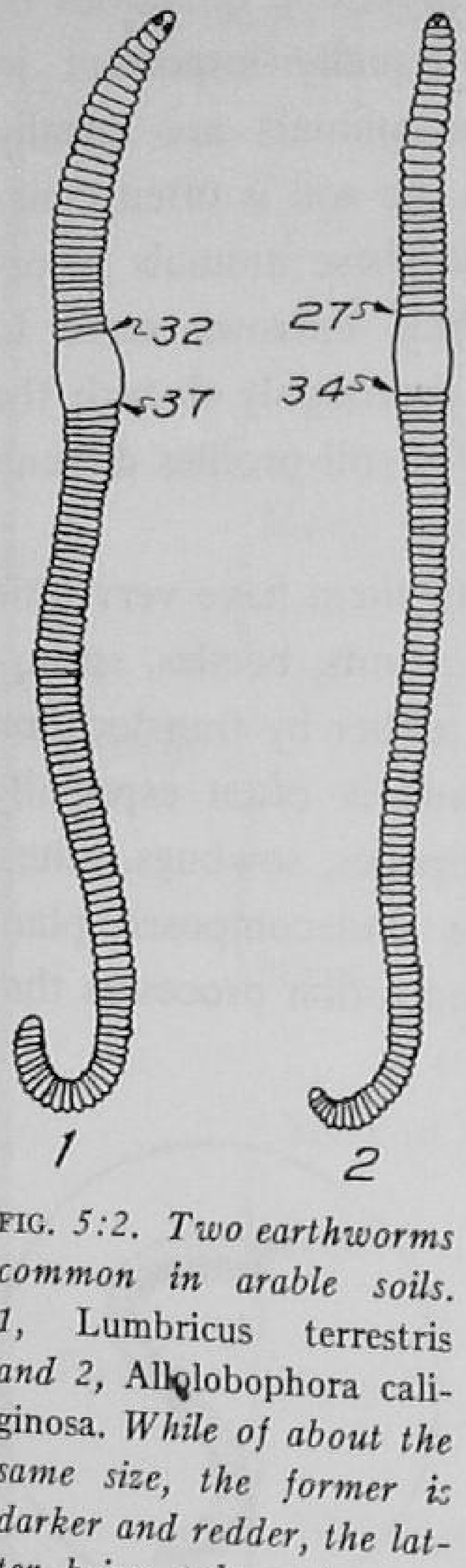

FIG. 5:2. *Two earthworms common in arable soils. 1,* Lumbricus terrestris *and 2,* Allolobophora caliginosa. *While of about the same size, the former is darker and redder, the latter being pale and somewhat pinkish. Also there is a difference in the mouth parts. And as the diagram shows, the girdles of the organisms are located somewhat differently in respect to the segments.*

5:2. EARTHWORMS

One of the most important of the macroanimals of the soil is the ordinary earthworm,[3] of which there are a number of species.[4] The *Lumbricus terrestris,* a reddish organism, and *Allolobophora caliginosa,* pale pinkish in color, are very common both in Europe and in eastern and central United States. (See Fig. 5:2.) In other parts of this country somewhat different species are dominant depending on the nature of the habitat. In the tropics and semi-tropics still other types are prevalent, some small and others surprisingly large. In respect to species, it is rather interesting to note that *Lumbricus terrestris* probably is not native to America but as the forests and prairies were put under cultivation, this European worm rapidly replaced the native types which could not withstand the changed conditions. Virgin lands, however, still retain, at least in part, their native populations.

Quantity of soil digested. That earthworms are important in many ways no one will deny.

[3] Walton, W. R., *Earthworms as Pests and Otherwise,* Farmers' Bulletin, 1569, U. S. Dept. of Agriculture, 1928.

[4] Gates, G. E., "The Earthworm Fauna of the United States," *Science,* 70: 266–267, 1929.

Eaton, T. H., Jr., "Earthworms of the Northeastern United States: A Key with Distribution Records," *Jour. Wash. Acad. Sci.,* 32: 242–249, 1942.

Darwin's patient research [5] covering many years indicates that the amount of soil that these creatures pass through their bodies annually may amount to as much as 15 tons of dry earth per acre, a startling figure. At such a rate, a mass of soil equivalent to the acre-furrow slice would be so processed in a period of only sixty or seventy years. During the passage through the worms, not only the organic matter, which serves the earthworm as food, but also the mineral constituents, are subjected to digestive enzymes and to a grinding action within the animals. The rank growth of grass around earthworm casts suggests an increased availability of plant nutrients therein. Nitrogen perhaps is most markedly affected.

Lunt and Jacobson [6] studied the earthworm casts on a cultivated field and also at three forest sites. The casts on the cultivated land at the time of examination weighed 16,000 pounds an acre. Compared to the soil itself, the casts were definitely higher in organic matter, total and nitrate nitrogen, exchangeable calcium and magnesium, available phosphorus, pH and percentage base saturation, and exchange capacity. The data for forest soils were even more striking. These results support the observation in the preceding paragraph regarding the increased growth of grass observed on and around earthworm casts.

Influence on soil fertility and productivity. Over sixty years ago, Wollny [7] conducted experiments with soil, in one case containing earthworms, and in another, free of them. Although there was much variation in his results, they were in every case in favor of the soil containing the worms. More recently Puh [8] conducted a similar experiment in China. The soil with the worms contained more organic matter at the end of the test period, the base-exchange capacity was higher, and the availability of the phosphorus and potash was increased. Moreover, the castings always had a higher pH than the original soil, a rather significant sidelight on the digestive influence of the worms. Still more recently Hopp and Slater [9]

[5] Darwin, Charles, *The Formation of Vegetable Mold,* D. Appleton-Century Company, Inc., New York, 1885.

[6] Lunt, H. A., and H. G. M. Jacobson, "The Chemical Composition of Earthworm Casts," *Soil Sci.,* 58: 367–375, 1944. The authors review the literature available on the subject.

[7] Wollny, E., "Untersuchung über die Beeinflussung der Fruchtbarkeit der Ackerkrume durch die Thätigkeit der Regenwürmer," *Forschungen a. d. Gebiete d. Agr.-Physik,* 13: 381–395, 1890.

[8] Puh, Y. C., "Beneficial Influence of Earthworms on Some Chemical Properties of the Soil," *Sci. Soc. China, Biol. Lab. Contrib.,* Zool. Ser., 15, No. 9: 147–155, 1941.

[9] Hopp, Henry, and C. S. Slater, "Influence of Earthworms on Soil Productivity," *Soil Sci.,* 66: 421–428, 1948.

obtained data that in general confirm the fertility conclusions cited above.

Other effects. Earthworms are important in other ways. The holes left in the soil serve to increase aeration and drainage, an important consideration in soil development. Moreover, the worms bring about a notable transportation of the lower soil to the surface. They also mix and granulate the soil by dragging into their burrows quantities of undecomposed organic matter, such as leaves and grass, to serve them as food and as protection. In some cases, the accumulation is surprisingly large. In uncultivated soils, this is more important than in plowed land where organic matter is turned under in quantity. Without a doubt, earthworms have in some cases, especially in virgin soils, definitely increased both the size and stability of the soil aggregates.[10]

Factors affecting earthworm numbers. Earthworms prefer a moist habitat. Therefore, they are found mostly in medium to heavy soils whose moisture capacity is high, rather than in those of a sandy, droughty nature. Moreover, they must have organic matter and they thrive best in land where this constituent is plentiful. It seems, also, that the nutrition of some earthworms depends on certain lime-secreting glands. Perhaps because of this, they are not usually found abundantly in soils that are low in replaceable calcium. There are some exceptions to this, however. Nevertheless, it is quite surprising to find how suddenly the earthworm population at times will change as to vigor, numbers, and even species within very short distances in response to pH and other soil conditions.

Russell[11] found that the numbers of earthworms were markedly affected by the application of farm manure. Considering their dependence upon organic matter and their response to fertility levels, this influence is to be expected. Russell quotes them as ranging from 13,000 per acre in a soil receiving no farm manure to over 1,000,000 per acre on land to which farm manure in quantity was applied. These data are in line with figures cited by Lutz and Chandler[12] indicative of a range under normal conditions of from 250,000 to at least 1,000,000 individuals to the acre.

[10] Dawson, R. C., "Earthworm Microbiology and the Formation of Water-Stable Aggregates," *Proc. Soil Sci. Soc. Amer.*, 12: 512–516, 1947. See also, Hopp, H., and H. T. Hopkins, "Earthworms as a Factor in the Formation of Water-Stable Aggregates," *Jour. Soil and Water Conservation*, 1: 11–13, 1946; and Gurjanowa, O. Z., "Effect of Earthworms and of Organic Fertilizers on Structure Formation in Chernozem Soils," *Pedology*, 4: 99–108, 1940.

[11] Russell, E. J., *Soil Conditions and Plant Growth*, Longmans, Green and Company, New York, 1932, p. 414.

[12] Lutz, H. J., and R. F. Chandler, Jr., *Forest Soils*, John Wiley and Sons, Inc., New York, 1948, p. 101.

Using Russell's data as to numbers and assuming each worm to weigh on the average ½ gram, the live weight of these animals would range from approximately 15 pounds per acre in the one case to over 1,100 pounds in the other. However, due to conditions presented by different soils and to variations in the size and species of worms present, these figures should be applied with caution. They are merely suggestive, but they do indicate what may be expected in a general way as to earthworm population weight in arable soils.

Earthworm ecology. In his study of earthworm ecology at College Park, Maryland, Hopp [13] found that these organisms (mostly *Helodrilus caliginosus* and *H. chloroticus*) followed a distinct reproductive cycle. In sod young earthworms were fewest in the spring and reach their peak in autumn. The numbers of mature worms were just reversed. In the fall before they become tolerant to cold, the new generation is easily killed by freezing. Hence, in bare, cultivated soils the population is often seriously reduced in late autumn by a sudden freeze unless the soil surface is covered by plant debris of some kind.[14] Frost damage is not so likely to occur in sodded land.

Therefore, in regions where soil freezing is the rule, a surface protection of some type is necessary as winter sets in if the earthworm population is to be carried over more or less intact. However, after the first severe weather, the earthworms not only acquire tolerance to the cold but also migrate to lower horizons where temperatures are more favorable. This penetration may range from 3 to 6 feet. For gardeners and others who wish to maintain a high earthworm population in their soils, surface protection is as essential as high organic matter, suitable moisture, good drainage and aeration, and low acidity.

5:3. SOIL MICROANIMALS

Of the abundant microscopic animal life in soils, two groups are particularly important—nematodes and protozoa. A third—the rotifers—at least deserves mention. The three groups will be considered in order. (See Table 5:1.)

Nematodes. Nematodes, threadworms, or eelworms as they are commonly called, are found in almost all soils, often in surprisingly large

[13] Hopp, Henry, "The Ecology of Earthworms in Cropland," *Proc. Soil Sci. Soc. Amer.*, 12: 503–507, 1947.

[14] Slater, C. S., and Henry Hopp, "Relation of Fall Protection to Earthworm Populations and Soil Physical Conditions," *Proc. Soil Sci. Soc. Amer.*, 12: 508–511, 1947.

numbers. A maximum of 50 to the gram of dry soil would mean about 45 billions to the acre-furrow-slice. These organisms are round and spindle-shaped in form, the caudal end usually being acutely pointed. In size, they are almost wholly microscopic, seldom being large enough to be seen at all readily with the naked eye. (See Fig. 5:3.)

Three groups of nematodes may be distinguished on the basis of their food demands: (1) those that live on decaying organic matter, (2) those that are predatory [15] on other nematodes, small earthworms, and the like, and (3) those that are parasitic, attacking the roots of higher plants to pass at least a part of their life cycle imbedded in such tissue. The first and second groups are by far the most numerous in the average soil and most varied.

The last group, however, especially those of the genus Heterodera [16] is the most important to the plant specialist. Due to their adaptable mouth-parts and pointed form they find it easy to penetrate plant tissue. The roots of practically all plants are more or less infested even in cool temperate regions,[17] and the damage done is often very great, especially to vegetable crops grown in southern United States. Even in greenhouses, nematodes may become a serious pest unless care is taken to avoid infestation. Due to the difficulties encountered in control, an appreciable nematode infection is a serious matter.[18]

Protozoa. Protozoa [19] probably are the simplest form of animal life. Although one-celled organisms, they are considerably larger than bacteria and of a distinctly higher organization. Some are merely masses of naked protoplasm—amoeba—while others exhibit a much higher development and are even protected with siliceous or chitinous coverings. For convenience of discussion, soil protozoa are divided into three groups: (1) amoeba, (2) ciliates or infusoria, and (3) flagellates. The presence

[15] Cobb, N. A., "The Mononchs, A Genus of Free-Living Predatory Nematodes," *Soil Sci.*, 3: 431–486, 1917.

[16] *Root-Infecting Eel Worms of the Genus Heterodera;* A Bibliography and Host List, Imp. Bur. Agr. Parasitology, St. Albans, 1931. Also, Goodey, T., *Soil and Fresh Water Nematodes*, John Wiley and Sons, New York, 1951.

[17] The infection of the potato soils of Long Island, New York, with the golden nematode (Heterodera Rostochiensis) is a case in point, threatening the economic production of potatoes on soils that otherwise are satisfactory both as to yield and as to proximity to market.

[18] Kincaid, R. R., "Soil Factors Affecting Incident of Root Knot," *Soil Sci.*, 61: 101–109, 1946.

[19] Sandon, H., *The Composition and Distribution of the Protozoan Fauna of the Soil*, Oliver and Boyd, Edinburgh, 1927.

of numerous cilia or hairs and of flagella, long whiplike appendages of protoplasm, are the bases for the two latter subdivisions. (See Fig. 5:3.) The flagellates are usually most numerous in soil followed in order by the amoeba and the ciliates.

The protozoa are the most varied and numerous in the microanimal population of soils. More than 250 species have been isolated, sometimes as many as 40 or 50 of such groups occurring in a single sample of soil. The presence of protozoa has been reported in soils from most of the countries of Europe, the United States, and many other regions. Many of these organisms are highly adaptable and occur in habitats other than that of the soil. A considerable number of serious animal and human diseases are due to protozoan infections.

The numbers of protozoa in the soil are subject to extreme fluctuation, even when conditions apparently are continuously favorable. Aeration, as well as the available food supply, is probably a very important factor. Most of the organisms are therefore confined to the surface horizons. Usually, the numbers are highest in the spring and autumn. Perhaps 1,000,-000 protozoa of all kinds per gram of a representative dry soil might be considered a maximum. This might amount to a live weight of 100 or even 200 pounds to the acre.

The nutritional habits of protozoa are not well known. No doubt, most of those in the soil depend on nonliving organic matter as a source of food. There are some indications, however, that certain groups may ingest bacteria and thus, in an indirect way, may interfere with higher plants. The ingestion of bacteria having to do with the availability of plant nutrients, might appreciably interfere with the growth of higher plants. For example, any marked check of ammonification or nitrification might be of serious practical concern.

Rotifers. That rotifers, the third group of microanimals to be considered, occur in the soil is well known and under moist conditions, especially in swampy land, their numbers may be great. As many as fifty different species have been found under such environs.These animals are mostly microscopic in size. Their anterior is modified into a retractile disk bearing circles of cilia which, in motion, give the appearance of moving wheels—hence, the name. These hairs sweep floating food materials into the animal. The posterior end of the rotifer tapers to a foot by which the rotifer can attach itself to convenient objects. (See Fig. 5:3.)

Just how important rotifers are in soils is unknown. No doubt they

enter into the cycle of organic dissolution in a more or less important way, especially in peat bogs and in wet places occurring in mineral soils.

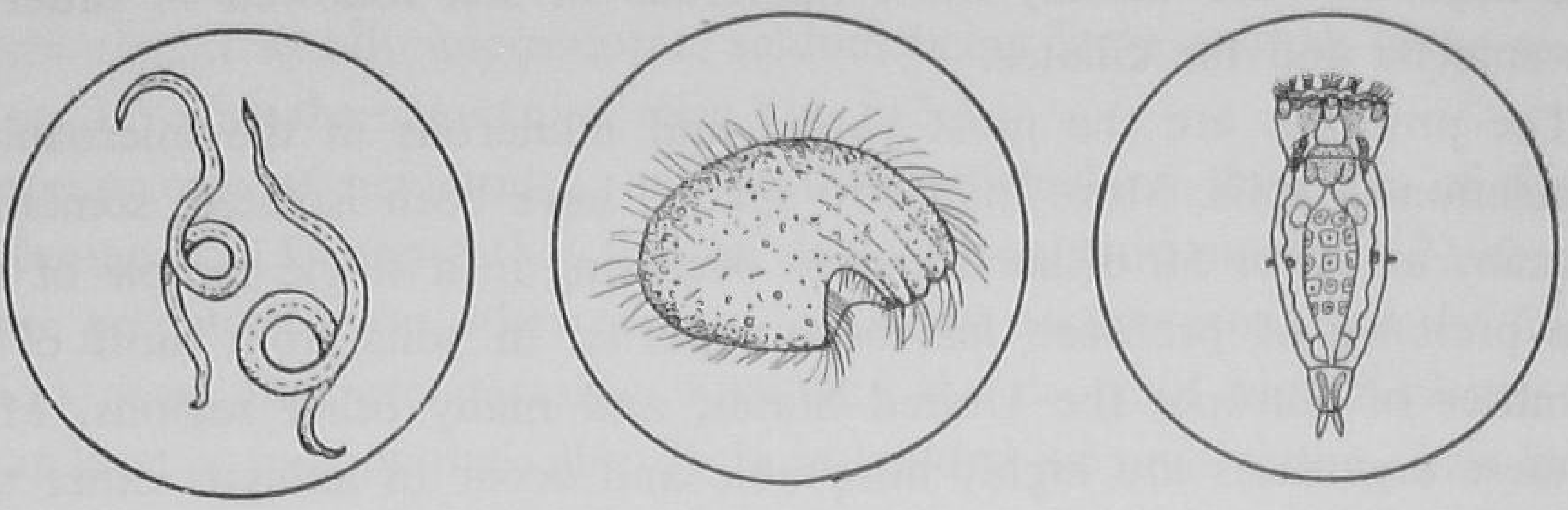

FIG. *5:3. Parasitic nematodes (left), a ciliated protozoan (center), and a common rotifier (right). (First two after Waksman.)*

5:4. PLANT LIFE OF THE SOIL

The organisms of a plant nature are more numerous and, from some standpoints, are more important than are the animal forms. This is true especially in respect to the final stages of organic matter decomposition, the synthesis of humus and the production of compounds simple enough for the direct nutrition of higher plants. It must be remembered, however, that the initial digestion is very often due to animals such as millipedes and springtails greatly assisted by earthworms if the lime content and other conditions of the organic residues are favorable.

The plant life of the soil will be considered under five heads as follows: (1) roots of higher plants, (2) algae, (3) fungi, (4) actinomycetes, and (5) bacteria. (See Table 5:1.)

5:5. ROOTS OF HIGHER PLANTS

As a source of organic matter, the roots of higher plants are of supreme importance since they supply much more original tissue than all of the other organisms combined. In fact, the life of the soil might be divided into two distinct and, in some respects, opposing groups—(1) those that supply organic residues and (2) those that are engaged primarily in tearing such residues down. Plant roots are, of course, the all-important representative of the first group, while millipedes, springtails, earthworms, bacteria, molds, and actinomycetes are principals in the second type of activity.

Amounts of organic tissue added. A good crop of oats will produce perhaps 4,000 pounds of dry matter to the acre in its aboveground parts,

while the figure for corn on the same basis would be about 6,000 pounds. If the roots left in the soil when such crops are harvested amount to even half these weights, the added organic residues are, by no means, inconsiderable. In fact, and this is a situation seldom appreciated even by farmers, the maintenance of a satisfactory supply of organic matter in arable soils is possible only because of root residues added in this automatic way. For a photo of elongating as well as dying rootlets see Figure 5:4.

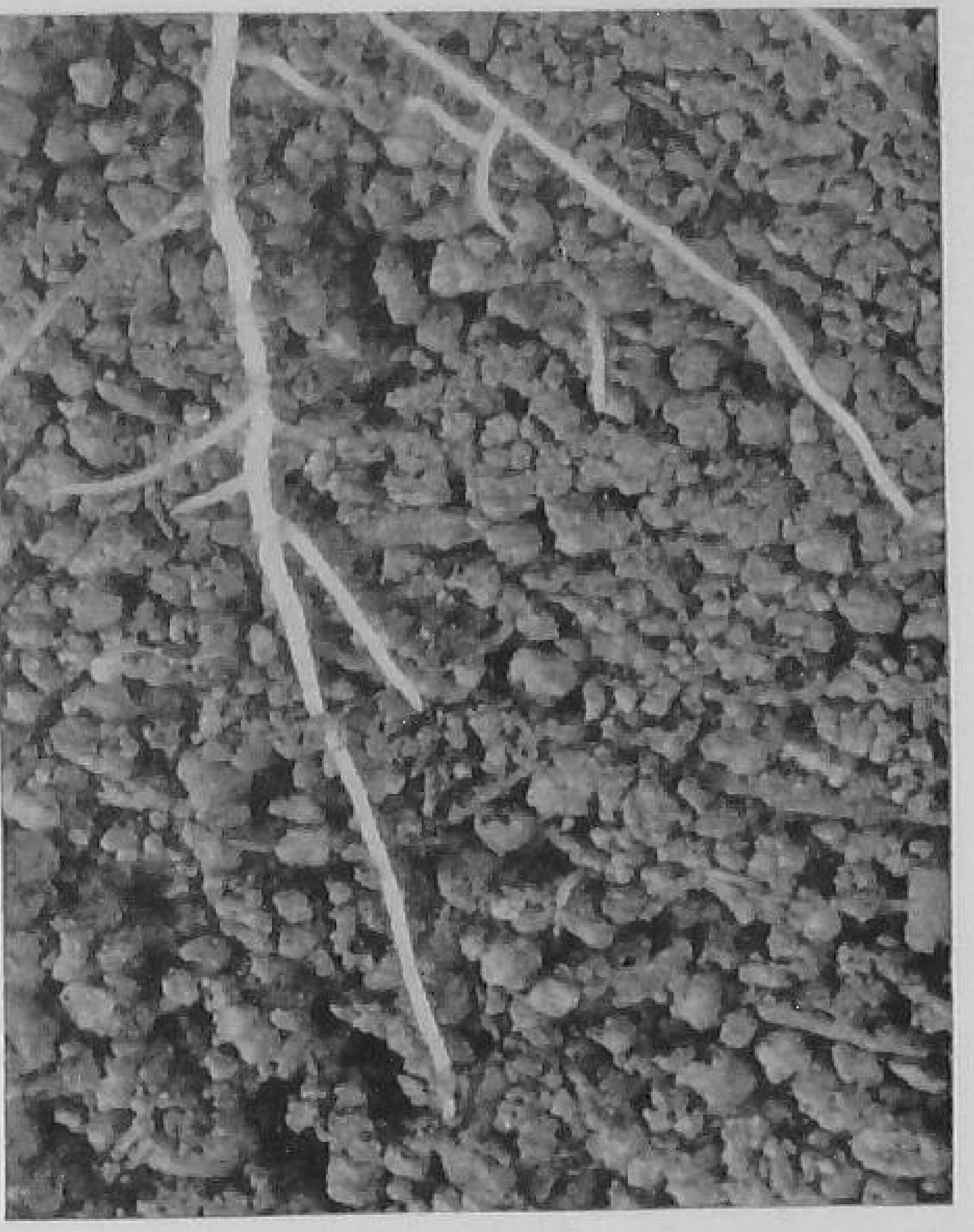

FIG. 5:4. *Rootlets elongate rapidly and thereby are continually establishing new soil contacts. Were it not for this ready extension, crops growing on well drained arable soils would soon suffer from lack of moisture as well as nutrients. Since the life of these shoots is very short, they continually contribute to the supply of readily decomposable tissue and greatly stimulate microbial activity. Note the excellent granulation of this soil. (N. Y. State College of Agriculture Photo.)*

The roots of higher plants also function in a more intimate manner than as a source of dead tissue for the nutrition of soil microbes. When alive, they not only influence the equilibrium of the soil solution by the withdrawal of soluble nutrients, but they also have something to do in a direct way with nutrient availability. Acids, especially carbonic, are concentrated at the root surfaces and hence become effective solvents. Again certain excretions as well as the sloughing of root tissue [20] undoubtedly locally stimulate the microflora to an intensity of action not attained in other parts of the soil.[21] This means that the adsorptive surfaces of the root hairs lie within the zone of unusual nutrient availability. This has already been

[20] Lyon, T. L., and J. K. Wilson, *Liberation of Organic Matter by Roots of Growing Plants,* Memoir 40, Cornell Univ. Agr. Exp. Sta., 1921.

[21] Wilson, J. K., and T. L. Lyon, *The Growth of Certain Microorganisms in Planted and Unplanted Soils,* Memoir 103, Cornell Univ. Agr. Exp. Sta., 1926.

Starkey, R. L., "Some Influence of the Development of Higher Plants upon the Microorganisms of the Soil: IV. Microscopic Examination of the Rhizosphere," *Soil Sci.,* 45: 207–227, 1938.

Timonin, M. I., "The Interaction of Higher Plants and Soil Microorganisms: III. Effect of By-products of Plant Growth on Activity of Fungi and Actinomyces," *Soil Sci.,* 52: 395–408, 1941.

explained (page 43) and indicates in part why the roots of higher plants are classified as soil organisms. They not only force a transfer of nutrients but they also promote an availability that, under other conditions, might be very slow.

5:6. THE MICRO-PLANT ORGANISMS—DIFFICULT TO STUDY

Before considering the specific groups of the micro-plant organisms it may be well to mention the inadequacies of the methods which have been used in their study. For example, it should be pointed out that the estimation of the numbers of specific organisms in the soil is often quite inaccurate. This is due to the fact that all soil microorganisms do not grow equally as well on the various artificial media commonly employed in making counts. A given species might function very well in the soil and yet grow poorly, if at all, on any of the media commonly used. Consequently, it would not be counted satisfactorily by this so-called plate method.

The above example is a reminder of the extreme complexity of the microbiological population making it difficult to study the specific functions of the various groups. These situations should be kept in mind constantly in reading the following sections.

5:7. SOIL ALGAE [22]

Most algae are chlorophyll-bearing organisms and, as such, must live at or very near the surface of the soil, if they are to survive in a habitat of this nature. However, certain forms seem able to obtain their energy largely from organic matter and may readily exist within and below the surface horizon. The number of these, however, is not large. Thus, some algae live and function much like higher plants, while others in their nutritional habits are typical soil microorganisms. Over sixty species have been isolated from soils, those most prominent being the same the world over. Soil algae are divided into three general groups: (1) blue-green, (2) green, and (3) diatoms.

Naturally, soil algae in vegetative form are most numerous in the surface layers, especially in the upper inch of arable soils. In subsoils, most algae

[22] A reliable summary is presented by Bristol-Roach, B. M., "The Present Position of Our Knowledge of the Distribution and Function of Algae in the Soil," *Proc. and Papers, First Internat. Cong. Soil Sci.*, 3: 30–38, Washington, 1928. See also Waksman, S. A., *Principles of Soil Microbiology*, The Williams and Wilkins Company, Baltimore, 1932.

are present as resting spores, or cysts, or in vegetative forms that do not depend upon chlorophyll. Grassland seems especially favorable for the blue-green forms, while in old gardens, diatoms are often numerous. All of the ordinary types of algae are greatly stimulated by the application of farm manure.

Both the green and the blue-green algae outnumber the diatoms, 100,000 to a gram of dry surface soil being an estimated minimum under favorable conditions for each in Rothamsted soils.[23] In certain Utah soils, Martin[24] reports the total algal population as reaching a maximum of 800,000 to a gram of dry soil.

Algae, no doubt, contribute to the organic content of the soil and may be valuable as a storage of energy during unfavorable periods due to their great vitality and powers of recovery. They are thought by some authors to encourage the fixation of nitrogen by certain bacteria. But if this should be true, it probably is of little importance.[25] The blue-green algae undoubtedly independently fix some atmospheric nitrogen[26] but, by no means, to the extent effected by bacteria except perhaps in special cases.[27] It would seem, therefore, that the most important role of algae, in general, is the aid they give to bacteria and fungi in the decomposition of plant tissue, the synthesis of humus and in the availability of plant nutrients.

5:8. SOIL FUNGI[28]

It is only within comparatively recent years that the importance of the role played by fungi in the soil has been recognized. While their influence

[23] Russell, E. J., *Soil Conditions and Plant Growth,* Longmans, Green and Company, New York, 1937, p. 420.

[24] Martin, Thomas L., "The Occurrence of Algae in Some Virgin Utah Soils," *Proc. Soil Sci. Soc. Amer.,* 4: 249, 1939.

[25] Stokes, J. L., "The Role of Algae in the Nitrogen Cycle of the Soil," *Soil Sci.,* 49: 265–275, 1940.

[26] Allison, F. E., and H. J. Morris, "Nitrogen Fixation by Blue-Green Algae," *Science,* 71, No. 1834: 221–223, 1930.

[27] Algae are especially numerous in rice soils and when such lands are waterlogged and exposed to the sun appreciable amounts of nitrogen are fixed by these organisms. Moreover, algae fixation is enhanced when the rice crop occupies the paddies. Apparently this stimulation is due to CO_2 which is at an especially high level when the rice plants are growing most vigorously. The nitrogen fixation by algae also is stimulated by phosphate fertilizers. See De, P. K., and M. Sulaiman, "Fixation of Nitrogen in Rice Soils by Algae as Influenced by Crop, CO_2 and Organic Substances," *Soil Sci.,* 70: 137–151, 1950.

[28] Gilman, J. C., *A Manual of Soil Fungi,* The Iowa State College Press, Ames, Iowa, 1945.
Waksman, S. A., "Three Decades with Soil Fungi," *Soil Sci.,* 58: 89–115, 1944. This article carries a rather complete bibliography.

is still by no means entirely understood, it is now known that they play a very important part in the transformations of the soil constituents. Over two hundred species have been identified representing forty-two genera. Like the bacteria and actinomycetes, fungi contain no chlorophyll and must depend for their energy and carbon on the organic matter of the soil.

The superficial characteristic that distinguishes fungi is the filamentous nature of their vegetative forms. Their mycelial threads may be simple and restricted or profusely branched and of such dimensions as to attract even casual attention. More than this, the special spore-forming or fruiting bodies often attain, with some groups, macroscopic sizes. Fungal organisms may thus vary from the simple microscopic yeasts to mushroom and bracket fungi of extraordinary dimensions.

For convenience of discussion, fungi may be divided into three groups as follows: (1) yeasts, (2) molds, and (3) mushroom fungi. Of these, only the last two are considered important in soils, as yeasts occur to a very limited extent in such a habitat. They, therefore, need not receive further consideration here.

Molds. The distinctly filamentous, microscopic, or semi-macroscopic fungi are commonly spoken of as molds. (See Fig. 5:5.) In soils, they play a role infinitely more important than the mushroom fungi, approaching or even excelling at times the influence of bacteria. They respond especially to soil aeration, their numbers and activities diminishing as air movement is retarded.

Molds will develop vigorously in acid, neutral, or alkaline soils, some being favored, rather than otherwise, by a lowered pH. (See Fig. 14:4.) Consequently, they are noticeably abundant in acid soils, where bacteria and actinomycetes offer only mild competition. Were it not for fungi, there would be little decomposition and digestion of the organic residues in acid forest soils other than that effected by millipedes, springtails, mites, and other animals.

Molds are found in all horizons of the soil profile, the greatest numbers being, of course, in the surface layers where organic matter is ample and aeration adequate. Many genera are represented, four of the more evident being Penicillium, Mucor, Trichoderma, and Aspergillus. Species from at least eight other genera often are plentiful, however. All of the common species occur in most soils, conditions determining which shall dominate. Their numbers fluctuate greatly with soil conditions, perhaps 1,000,000

individuals to the gram of dry soil representing a more or less normal population.[29] This might well amount to 1,000 or 1,200 pounds of living organisms to the acre.

Perhaps the most important factor relating to the activity of fungi is food supply. The addition of almost any kind of decomposable organic matter to the soil, especially farm manure, has a surprising effect on mycelial development. Even commercial fertilizers increase the number of molds present. When conditions are unfavorable, the vegetative tissue diminishes, and spores are formed which have great powers of resistance. Molds are an important part of the general-purpose, heterotrophic group of soil organisms that fluctuate so greatly in most soils.

In this connection it is interesting to note that fungal population is constantly changing not only in numbers but in respect to the species dominant. The type of food, or more significantly the stage of decay of the soil organic matter, seems to determine, at least in part, the particular mold or molds prevalent.[30]

Activities of fungi. It is hardly necessary to state again that fungi are of paramount importance in soils. In their ability to decompose organic residues they are the most versatile and perhaps the most persistent of any group. Cellulose, starch, gums, lignin, as well as the more easily affected proteins and sugars, readily succumb to their attack. In respect to the processes preparatory to humus formation,[31] molds are perhaps more important than bacteria. This is certainly true in acid forest soils.

Moreover, fungi function more economically than bacteria in that they transform into their tissues a larger proportion of the carbon and nitrogen of the compounds attacked and give off as by-products less carbon dioxide

[29] Brierley, W. B., S. T. Jewson, and M. Brierley, "The Quantitative Study of Soil Fungi," *Proc. and Papers, First Internat. Cong. Soil Sci.*, 3: 48–71, 1928.

[30] Martin working with Utah soils found when starches and sugars were available that species of *Mucor* and *Rhizopus* were especially abundant. Later in the decay process when these foods were gone, the more stable cellulose and hemicellulose seemed to encourage *Penicillium glaucum* and *Aspergillus niger*. Still later, when humification was more or less complete and lignin materials were the major food supply, *Aspergillus minutis* and species of *Alternaria* and *Cladosporium* were dominant. Truly the situation is kaleidoscopic. Martin, T. L., D. A. Anderson, and Rex Goates, "Influence of the Chemical Composition of Organic Matter on the Development of Mold Flora," *Soil Sci.*, 54: 297–302, 1942.

[31] It is now known that certain types of fungi synthesize lignin in considerable amounts. Thus these groups not only encourage humus formation by preparing plant residues for interaction but they also produce the stabilizing substance themselves. Hence in encouraging soil granulation fungi should be in general even more effective than bacteria. Pinck, L. A., and F. E. Allison, "The Synthesis of Lignin-like Complexes by Fungi," *Soil Sci.*, 57: 155–161, 1944.

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rather closely. On the basis of organization, actinomycetes occupy a position between true molds and bacteria. Although they often are classified with the fungi, they are sometimes called thread bacteria. (See Fig. 5:5.)

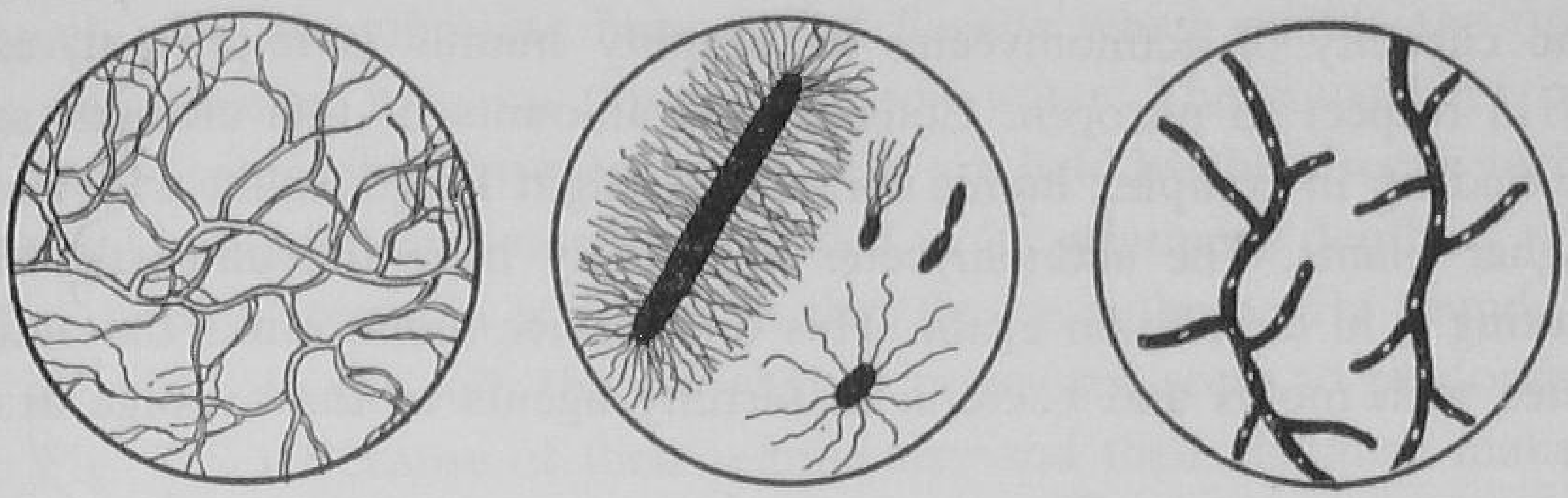

FIG. *5:5. The three most important plant microorganisms of the soil, from left to right, Fungal mycelium, various types of bacterial cells, and actinomycetes threads. The bacteria and actinomycetes are much more highly magnified than the fungi.*

Actinomycetes develop best in moist, well-aerated soil. But in times of drought, they remain active to a degree not generally exhibited by either bacteria or molds. They are in general rather sensitive to acid soil conditions, their growth being practically prohibited in mineral soils at a pH of 5.0 or below. Their optimum development occurs at pH values between 6.0 and 7.5. (See Fig. 14:4.) This marked relationship to soil reaction is sometimes taken advantage of in practice, especially in respect to potato scab, an actinomycetes disease of wide distribution. It is often possible by the use of sulfur to effect a reduction in pH sufficient to keep the disease under control. (See page 413.)

Numbers and activities of actinomycetes. Except for bacteria, no other microorganisms are so numerous in the soil as the actinomycetes, their numbers sometimes reaching 15 or perhaps 20 millions to a gram of dry soil. In actual live weight, they often excel bacteria but, by no means, equal in weight the amount of fungal tissue normally present. Under especially favorable conditions, perhaps 500 to 600 pounds of actinomycetes threads and spores might be present in an acre-furrow-slice. These organisms are especially numerous in soils high in humus such as old meadows or pastures when the acidity is not too great. There they sometimes exceed in numbers all other microscopic forms of life. The addition of farm manure markedly stimulates their activities. The aroma of freshly plowed land, that is so noticeable at certain times of the year, is probably due to actinomycetes, as well as to certain molds.

Actinomycetes undoubtedly are of great importance in respect to the dissolution of soil organic matter and the liberation of nutrients therefrom. Apparently, they reduce to simpler forms even the more resistant compounds such as lignin. The presence of actinomycetes in such abundance in soils long under sod is some indication of this latter capacity.

The capacity of actinomycetes to simplify humus is important, especially in respect to nitrogen. Considerable amounts of this element seem to be tied up in complex humic forms and might long remain unavailable to higher plants. The actinomycetes apparently have the unusual ability of putting it in circulation again. This one service alone ranks the actinomycetes with molds and bacteria as fertility agents in the average arable soil.

5:10. SOIL BACTERIA [34]

A better knowledge has been gained of bacteria than of any of the other microorganisms common in soils. And as a result, they have been considered, until recent years, the most important class. But as more becomes known of the other forms of life, scientists are beginning to question whether the fungi and perhaps certain of the animals, may not, at times, equal or even outrank the bacteria.

Characteristics. Bacteria are single-cell organisms, one of the simplest and smallest forms of life known. They multiply by elongating and dividing into two parts. They are, therefore, often called *fission* fungi. The process is, under favorable conditions, surprisingly rapid. A new organism may develop in twenty or thirty minutes with ease. This almost unlimited capacity to increase in numbers is extremely important in soils. It allows certain groups quickly to assume their normal functions under favorable conditions, even though their numbers were originally small.[35]

Bacteria may thus be considered as a force of tremendous magnitude in the soil, held more or less in check by food supply, competition, and other conditions, but ever ready to exert an influence of profound importance. They, with the fungi and actinomycetes, largely make up that

[34] For a more thorough discussion of soil bacteria consult Waksman, S. A., *Principles of Soil Microbiology*, The Williams and Wilkins Company, Baltimore, 1932.

[35] If a single bacterium and every subsequent organism produced subdivided every hour, the offspring from the original cell would be about 17,000,000 in twenty-four hours. In six days, the organisms theoretically would greatly surpass the earth in volume.

general-purpose group of microorganisms, already mentioned, that fluctuates so markedly in response to soil conditions.

Bacteria are very small, the larger individuals seldom exceeding 4 or 5 microns (0.004 to 0.005 mm.) in length while the smaller ones approach the size of an average clay particle. Many soil bacteria are equipped with extremely delicate vibrating hairs called *flagella* which enable the organisms, on occasion, to swim through the soil water. This movement probably occurs sparingly, however, as the cells are held by the viscous surfaces of the soil colloidal mass or are imbedded in its gelatinous depths.

The shape of bacteria is varied in that they may be nearly round, rod-like, or spiral. In the soil, the rod-shaped organisms seem to predominate. (See Fig. 5:5.) Because of their minute size and their chemical make-up, bacteria, as well as other soil microorganisms, are highly colloidal in respect to both their cell wall and cell contents. This has much to do with their remarkable biochemical activity.[36]

Bacterial population in soils. The numbers of bacteria present in soil are variable, as many conditions markedly affect their growth. In general, the greatest population is in the surface horizons, since conditions of temperature, moisture, aeration, and food are here more favorable. It is fairly certain that the numbers of bacteria in soil are very large, possibly ranging as high as three or four billions [37] to a gram of soil. Four or five hundred pounds of live weight bacterial tissue to the acre-furrow-slice is probably a modest estimate.[38] Good soils seem, in general, to carry the greatest numbers. The bacterial flora, as well as the other soil organisms, fluctuates markedly with season, the numbers in humid temperate regions usually being the greatest in early summer and in the autumn.

In the soil, bacteria exists as mats, clumps, and filaments, called *colonies,* on and around the soil particles wherever food and other conditions are

[36] The surface exposed by soil bacteria is remarkable. Assuming that a single bacterium is, on the average, 1μ long by 0.5μ thick and that one billion are present to 1 gm. of soil, the external surface exposed would amount to about 10 sq. ft. to the pound of dry soil, or about 460 acres to the acre-furrow-slice.

[37] Thornton, H. G., and P. H. Gray, "The Numbers of Bacterial Cells in Field Soils, as Estimated by the Ratio Method," *Proc. Roy. Soc. London,* Ser. B, 115: 522–543, 1934.

[38] Thornton estimated the bacterial substance, both dead and alive, in the furrow-slice of the Barnfield soil, Rothamsted Experiment Station, as ranging from 1,500 to 5,600 pounds. This estimate is based on his improved method of determining numbers, which indicates that bacteria are more numerous in the soil than once supposed. See Russell, E. J., *Soil Conditions and Plant Growth,* Longmans, Green and Company, New York, 1932, p. 397.

favorable. The jelly-like mixture of mineral and organic colloidal matter makes an almost ideal medium for their development. While natural and artificial forces tend to distribute the organisms through the soil, most colonies enlarge, function, and die out in more or less their original position. Their existence depends on soil conditions, particularly food supply. Thus, there is a constant and rapid fluctuation—multiplication and death, often by starvation.

Many of the soil bacteria are able to produce spores or similar resistant bodies, thus presenting both a vegetative and a resting stage. This latter capacity is important as it allows the organisms more readily to survive unfavorable conditions.

Source of energy. Soil bacteria are commonly classified under two heads, *autotrophic* and *heterotrophic*. The former obtain their energy from the oxidation of mineral constituents, such as ammonium, sulfur, and iron, and most of their carbon from carbon dioxide. In numbers, they are comparatively insignificant, but since they include the organisms that support nitrification and sulfur oxidation, they are tremendously important in the sustenance of higher plants.

Most soil bacteria, however, are heterotrophic, that is, their energy and carbon both come directly from the soil organic matter. The general-purpose decay and ammonifying bacteria, as well as the fungi and actinomycetes, are all heterotrophic in character.

Importance of bacteria. The attention paid by man to the various conditions influencing the growth of bacteria is far beyond that usually allotted to other forms of soil life. One need not look far for the reasons. In the first place bacteria, as a group, almost without exception participate vigorously in all of the organic transactions so vital if a soil is to successfully support higher plants. They not only rival but they often excel both fungi and actinomycetes in this regard. Secondly, they hold, for all practical purposes, monopolies on three basic enzymic transformations, (1) *nitrification,* (2) *sulfur oxidation,* and (3) *nitrogen fixation.* If these were to fail, life for higher plants and for animals would soon fade out. Looked at from this angle, bacteria, the simplest and most numerous of all life-forms, are perhaps basically the most consequential.

5:11. CONDITIONS AFFECTING THE GROWTH OF SOIL BACTERIA [39]

Many conditions of the soil affect the growth of bacteria. Among the most important of these are the supplies of oxygen and moisture, the temperature, the amount and nature of the soil organic matter, and the H-ion concentration of the soil solution as well as the amount of exchangeable calcium present. These effects are briefly outlined below:

1. Oxygen requirements
   a. Some bacteria use mostly oxygen gas (Aerobic).
   b. Some use mostly combined oxygen (Anaerobic).
   c. Some use either of the above forms (Facultative).
   d. All three of the above types usually function in a soil at one time.
2. Moisture relationships.
   a. Optimum moisture level for higher plants usually best for most bacteria.
   b. The moisture content affects oxygen supply (see 1 above).
3. Suitable Temperature range
   a. From 70°–100° F., bacterial activity generally the greatest.
   b. Ordinary soil temperature extremes seldom kill bacteria.
4. Organic Matter requirements
   a. Used as energy source for majority of bacteria (heterotrophic).
   b. Organic matter not required as energy source for others (autotrophic).
5. Exchangeable Calcium and pH relationships
   a. High Ca, pH from 6–8 generally best for most bacteria.
   b. Calcium and pH values determine the specific bacteria present.
   c. Certain bacteria function at very low pH (3.0±) and others at high pH values.
   d. Exchangeable Ca seems to be more important than pH.

5:12. INJURIOUS EFFECTS OF SOIL ORGANISMS ON HIGHER PLANTS

Soil fauna. It has already been suggested that certain of the soil fauna are injurious to higher plants. For instance, rodents and moles may, in certain cases, greatly damage crops. Snails and slugs in some climates are exceedingly important pests, while the activity of ants, especially as to their transfer and care of aphis on certain plants, must be diligently combated by gardeners. Also, most plant roots are infested with eelworms,

[39] Useful supplementary reading on these factors will be found in Russell, E. J., and E. W. Russell, *Soil Conditions and Plant Growth*, Longmans, Green and Co., New York, 1950, especially Chap. 12.
Also see Waksman, S. A., *Principles of Soil Microbiology*, The Williams and Wilkins Company, Baltimore, 1932.

sometimes so seriously as to make the successful growth of certain crops both difficult and expensive. Protozoa, even though their effect may be indirect, also can promote a serious adverse influence.

Microflora and plant diseases. However, it is the plant forms of soil life that, in general, exert the most devastating effects on higher plants. All three groups—bacteria, fungi, and actinomycetes—contribute their quota of plant diseases. Some of the more common diseases produced by soil flora are: wilts, damping off, root rots, clubroot of cabbage and similar crops, and the actinomycetes scab of potatoes. In short, disease infestations occur in great variety, induced by many different organisms.

Injurious organisms live for variable periods in the soil. Some of them will disappear within a few years if their host plants are not grown, but others are able to maintain existence on almost any organic substance. Once a soil is infested, it is likely to remain so for a long time. Infection usually occurs easily. Organisms from infested fields may be carried on implements, plants, or rubbish of any kind. Even stable manure containing infected plants or the feces resulting from the feeding of such plants to animals act as disease carriers. Erosion, if soil is washed from one field to another, may be a means of transfer.

Disease control by soil management. Prevention is one of the best defenses against diseases produced by such soil organisms, hence the strict quarantines often attempted. Once a disease has procured a foothold, it is often very difficult to eradicate it. Rotation of crops is adequate for some diseases, but the entire absence of the host plant is often necessary.

The regulation of the pH is effective to a certain extent with potato scab and the clubroot of cabbage. If the pH is held somewhat below 5.3 or even 5.5, the former disease, which is due to an actinomycete, is much retarded. With clubroot, a fungus disease, the addition of hydroxide of lime until the pH of the soil is definitely above 7.0 seems fairly effective but is objectionable with certain types of rotation.

Steam sterilization is a practical method of treating greenhouse soils for a number of diseases. The breeding of plants immune to particular diseases has been successful in the case of the cowpea, cotton, and a number of other crops.

Competition for nutrients. Another way in which soil organisms may detrimentally affect higher plants, at least temporarily, is by competition for available nutrients. Nitrogen is the element usually most vigorously contested for, although organisms may utilize appreciable quantities of

phosphorus, potash, and lime to the exclusion of the crops growing on the land. Competition for trace elements may even be serious. Soil organisms usually exact their nutrient quota first and higher plants must subsist, if they can, on what remains available.[40]

A case of induced nutrient competition that is very common and exceedingly important occurs as follows: When a soil containing nitrates in amounts adequate for the vigorous growth of crop plants is treated with organic matter high in easily decomposable carbohydrates, such as strawy farm manure or a nonleguminous green manure low in nitrogen, tremendous biological activity is initiated. The general-purpose decay organisms, especially the fungi and bacteria, having a plentiful source of energy at their command, multiply rapidly. And as they must have nitrogen for the synthesis of new protoplasm, they use that which otherwise would go to the crop occupying the land. Nitrate and ammoniacal forms of nitrogen disappear and, until the decay organisms in part destroy the added organic matter and diminish in numbers, the higher plants face a serious nutritional situation, especially in respect to nitrogen. This relationship will be dealt with more fully later (see page 166) since it is so vital in respect to organic matter maintenance and nitrogen availability.

5:13. COMPETITION BETWEEN SOIL MICROORGANISMS[41]

The case cited in the preceding paragraph illustrative of the competition between microorganisms and higher plants serves also as an example of intense intermicrobial rivalry for food. Here the vigorous heterotrophic soil organisms (bacteria, fungi, and actinomycetes) entirely supersede the less numerous autotrophic bacteria who suffer eclipse until the rapid decay processes have spent their forces and humification is well advanced. Only then may the autotrophic bacteria function with any degree of vigor.

[40] Assuming that microbial tissue contains on the dry basis an average of 2.50 per cent P_2O_5, 10 per cent N, 0.60 per cent K_2O, and 0.60 per cent CaO, the synthesis of 500 lb. of such material dry (equal to approximately 1 ton of live-weight organisms) would require the equivalent of about 80 lb. of 16 per cent superphosphate, 312 lb. of commercial nitrate of soda, and 6 lb. each of commercial muriate of potash and ground limestone. Obviously, the feeding of the soil microorganisms is a problem in itself.

[41] Weindling, Richard, "Microbial Antagonism and Disease Control," *Soil Sci.*, 61: 23–30, 1946.

Nickell, L. G., and P. R. Burkholder, "Inhibition of Azotobacter by Soil Actinomycetes," *Jour. Amer. Soc. Agron.*, 39: 771–779, 1947.

Waksman, S. A., *Microbial Antagonisms and Antibiotic Substances*, The Commonwealth Fund, New York, 1947.

Undoubtedly, such food competition is the rule and not the exception in soils. In fact, microbial activity therein may be characterized as a series of contests for food in which certain organisms enjoy a temporary domination and certain others suffer temporary suppression. Life in the soil is far from harmonious.

Antibiotics produced in soils. Besides the food competition just stressed, there is another type of microbial rivalry just as intense and even more deadly. Certain bacteria, fungi, and actinomycetes have the capacity of producing substances that will inhibit, or even actually kill, other microbes. Not only are organisms alien to the soil thus affected but also many of those that normally flourish vigorously therein. In other words, here is a type of competition—apparently more or less independent of food supply—regarding which we need much more information, especially as to its operation within the soil. The capacity of certain organisms to lay down chemical barrages, which insure their own dominance within a restricted area, is an unique situation. It adds immeasurably to the difficulty of forecasting the trend of microorganic influences.

The discovery that many soil organisms can produce *antibiotics,* as they are called, has in some respects revolutionized the treatment of certain human and animal diseases, greatly minimizing their seriousness. Several preparations carrying specific bactericidal ingredients are now on the market such as penicillin and streptomycin. Undoubtedly, many new and valuable substances of this type are yet to be discovered. Although the soil harbors numerous types of disease organisms, it at the same time supports others that are the source of life-saving drugs, the discovery of which marks an epochal advance in medical science.

In addition to the competition among the microorganisms mentioned above it should be pointed out that they are often mutually helpful. Certain groups yield metabolic products which are used by others as a source of food. Perhaps the most evident example of this is the release by general-purpose decay organisms of ammonium ions which are used as a source of food and energy by the other organisms especially the nitrifiers.

5:14. ACTIVITIES OF SOIL ORGANISMS BENEFICIAL TO HIGHER PLANTS[42]

In their influence on crop production, the soil fauna and flora are, of course, indispensible. Not only do these organisms influence the soil physically, but they are the main driving forces which convert the insoluble and unavailable nutrients into forms which the plant may use. All of the waste materials which become a part of the soil are gradually resolved into simple products and humus. This humus, although the most resistant part of the organic residues, is itself finally destroyed by microbial effort. All forms of soil organisms, both animal and plant, have something to do with these processes of dissolution.

Carbon dioxide has already been specified as the source of carbonic acid, that all-important acid which has so much to do with ionic exchange, with the loss of lime in drainage and with the H-ion concentration of the soil solution. It also has been stressed as a source of carbonates and bicarbonates and as supplying carbon for autotrophic soil microorganisms and for higher plants. The presence of this gas is not an indication merely of organic matter dissolution but of energy liberation and utilization by the flora and fauna of the soil. In fact, the rate of carbon dioxide evolution is a rough measure of microbial activity.

Inorganic transformations. The appearance in the soil of ammonium compounds and nitrates is the result of a long series of biochemical transfers beginning with proteins and related compounds. (See page 155.) These successive changes are of vital importance to higher plants, since the latter adsorb most of their nitrogen in ammoniacal and nitrate forms. Reduce or cut them off and higher plants must suffer.

The production of sulfates is roughly analogous to the biological simplification of the nitrogen. (See page 156.) Here again a complicated chain of enzymic activities culminates in a simple soluble product—in this case the sulfate. This is the only important form in which sulfur may enter higher plants in appreciable amounts. Fortunately the microbial competition for sulfur usually is not as keen as that for nitrogen, hence sulfates are not likely to be as critical in cropped soils as are the simple compounds of nitrogen.

[42] The following article dealing with many of the phases already discussed is well worth reading if a person is interested in pursuing further the microorganic-higher plant relationships: Norman, A. G., "Recent Advances in Soil Microbiology," *Proc. Soil Sci. Soc. Amer.*, 11: 9–15, 1946.

Nitrogen fixation. An outstanding relationship of tremendous practical import is the fixation of elemental nitrogen. Such nitrogen, so plentiful in the atmospheric air, cannot be used directly by higher plants. It must be in combined form before it can satisfy their nutritional needs. Two groups of bacteria participate in the capture of gaseous nitrogen: the *nodule organisms,* especially those of legumes, and the so-called *free-fixing* bacteria of several kinds.

The legume bacteria, as they are often called, use the carbohydrates of their hosts as an energy source, fix the nitrogen, and pass part of it on to the infected host. However, some is left in the root tissue and in the sloughed nodules (see Fig. 16:3). This is likely to appear later in ammoniacal and nitrate forms due to the enzymic influence of other microbial organisms.

The free-fixing soil bacteria acquire their energy from the soil organic matter, fix the free nitrogen, and make it a part of their own tissue. When they die, decay, ammonification and nitrification render at least a part of this air nitrogen available to higher plants. Although nitrogen-fixing organisms are special purpose as to the transfer of nitrogen, they are, unlike the nitrifiers and sulfur oxidizers, heterotrophic since their energy and carbon apparently come exclusively from organic matter of various kinds.

It is obvious that the organisms of the soil must have energy and nutrients if they are to function efficiently. In obtaining them they break down organic matter, aid in the production of humus, and leave behind compounds that are useful to higher plants. These biotic features and their practical significance are considered in the next chapter which deals with soil organic matter.

CHAPTER

6 The Organic Matter of Mineral Soils[1]

IN SOIL genesis the presence of decomposing organic matter is a sign that synthesizing processes are well begun and that biochemical activities are supplementing those of a purely chemical nature. Under suitable climatic conditions plant and animal life soon gains a foothold in the weathering parent materials. As generations pass, organic residues are left to decay and mix with the decomposing mineral mass. This relationship becomes more and more intimate as time goes on, and the soil, as a natural body, is gradually evolved. It exhibits characteristic profile traits only when organic matter has become an integral part of its surface layers and has influenced the subhorizons as well.

6:1. THE SOURCES OF SOIL ORGANIC MATTER

The original source of the soil organic matter is, of course, plant tissue. Under natural conditions, trees, shrubs, grasses and other native plants supply annually large quantities of organic residues, both tops and roots. On arable soils, a good portion of the plants are commonly removed, but some residues, especially the roots, are left in the soil. Such materials, as they are decomposed and digested by soil organisms of many kinds, later become a part of the underlying horizons by infiltration or by actual physical incorporation.

Animals are usually considered as secondary sources of organic matter. As they work over the original plant tissues, they contribute waste products

[1] For a review of recent information on the components of soil organic matter, see Bremner, J. M., "A Review of Recent Work on Soil Organic Matter, Part I," *Jour. of Soil Sci.*, 2: 67–82, 1951.

and also donate their own bodies as their life cycles are consummated. Certain forms of animal life, especially the earthworms, centipedes, and ants, also play an important role in the translocation of plant residues.

6:2. THE COMPOSITION OF HIGHER-PLANT TISSUE

About 75 per cent, or even more, of average green tissue of higher plants is water. The dry substance thereof is made up of carbon, oxygen, hydrogen, nitrogen and mineral matter. (See Fig. 6:1.) Although over 90 per cent of the dry matter is carbon, oxygen, and hydrogen, the other elements play a vital role in plant nutrition. Nitrogen, sulfur, phosphorus, potassium, and calcium from organic sources are particularly important. A very large proportion of the soil nitrogen originally became a part of the solum as a constituent of the tissue of plants and animals.

The actual compounds in plant tissue are many and varied. (See Table 6:1.) The general composition of representative mature and dry plant tissue has been estimated to be about as follows: [2]

Carbohydrates	Sugars and starches	1– 5%
	Hemicelluloses	10–28%
	Cellulose	20–50%
Fats, waxes, Tannins, etc.		1– 8%
Lignins		10–30%
Proteins	Simple water soluble & crude proteins	1–15%

It should be emphasized that these figures are very general and serve only to give an idea of the range of those constituents commonly encountered in plant material.

The carbohydrates range in complexity from simple sugars to the celluloses and are made up of carbon, hydrogen, and oxygen. The fats and oils are glycerides of fatty acids such as butyric, stearic, oleic, etc. These are associated with resins of many kinds and are somewhat more complex than most of the carbohydrates. They too, are made up mostly of carbon, hydrogen, and oxygen.

Of the various groups, however, the proteins are probably the most complicated. They carry not only carbon, hydrogen, and oxygen, but also nitrogen and such elements as sulfur, iron, phosphorus, and others in lesser

[2] These figures are essentially the same as those given by Waksman, S. A., *Humus*, The Williams and Wilkins Company, Baltimore, 1938, p. 95.

amounts. They are compounds of high molecular weight and many are of unknown constitution. Simple and conjugated proteins, such as albumin, globulin, nucleoprotein, and phosphoprotein, are present in plants, besides such derived compounds as proteoses and peptones of many kinds. In addition, there are the complex and varied peptides, amino acids, and alkaloids.

6:3. THE DECOMPOSITION OF ORGANIC TISSUE AND THE PRODUCTS OF DECAY[3]

It is evident from the above statements that the chemical nature of plant tissue is very complicated. Hence, its addition to the soil must set up reactions of a decidedly complex order. Moreover, a considerable proportion of these residues is in the colloidal state. This adds still more to the difficulty of their study, especially as to the successive changes to which they are subject in the soil.

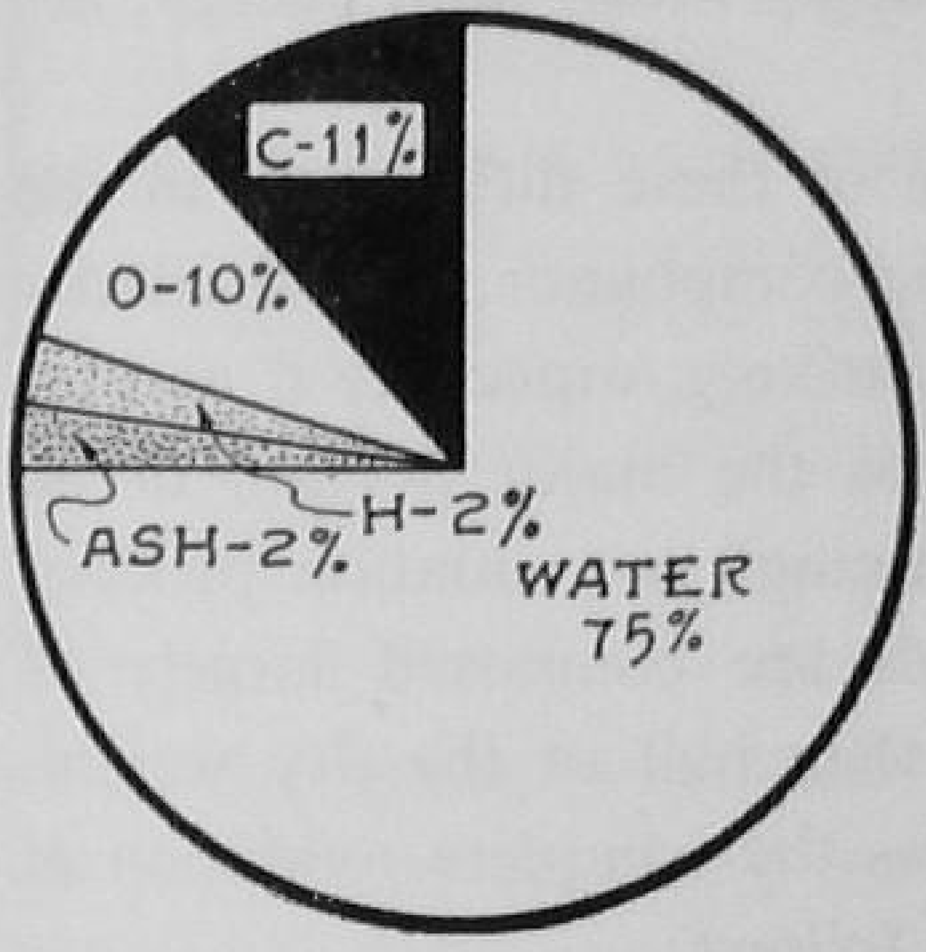

FIG. 6:1. *Diagram showing the generalized composition of green plant tissue. The nitrogen is included in the ash. Plant tissue is made up largely of carbon, hydrogen, and oxygen. (After Stoddard.)*

The decay of this heterogeneous material, even though some simple compounds are immediately in evidence, gives rise, even in the beginning, to residues which are amazingly complex. Hence, identification of individual substances is in general very uncertain. It is only when the processes are more or less consummated that simple compounds other than carbon dioxide and water are produced in abundance. (See Table 6:1.)

Rate of decomposition. Regardless of the complexity of the original tissues, it is possible to say something in respect to the relative resistance of their various organic groups to decomposition—a phase of great practical significance. The compounds found in plant tissue may be listed in terms of their ease of decomposition as follows:

[3] Waksman, S. A., *Principles of Soil Microbiology*, The Williams and Wilkins Company, Baltimore, 1932, Chaps. 16 and 17.
Russell, E. J., and E. W. Russell, *Soil Conditions and Plant Growth*, Longmans, Green and Company, New York, 1950, Chap. 14.
Waksman, S. A., "The Microbiologist Looks at Soil Organic Matter," *Proc. Soil Sci. Soc. Amer.*, 7: 16–21. 1942.

1. Sugars, starches, and simple proteins	rapidly decomposed
2. Crude proteins	↑
3. Hemicelluloses	
4. Cellulose	↓
5. Lignins, fats, waxes, etc.	very slowly decomposed

It should be remembered that all these compounds are usually decomposing simultaneously when fresh plant tissue is added to a soil. The rate at which decomposition occurs, however, decreases as one moves from the top to the bottom of the list. Thus, sugars and water-soluble proteins are examples of readily available energy sources for soil organisms. Lignins, on the other hand, although they eventually supply much total energy, are a very resistant source of food.

Decomposition a burning process. In spite of these differences in the rates of decomposition of the various organic compounds, the similarity of the ultimate end products of decay is quite striking, especially if aerobic organisms are involved. Under such conditions the major portion of all these compounds undergoes essentially a "burning" or oxidation process. The oxidizable fractions of organic materials are composed largely of carbon and hydrogen, which make up more than half of the dry weight. (See Fig. 6:1.) Consequently, we may express the complete oxidation of most of the organic compounds in the soil as follows:

$$\underset{\text{Carbon \& hydrogen containing compounds}}{\text{—[C, H]}} + O_2 \xrightarrow[\text{Oxidation}]{\text{Enzymic}} CO_2 + H_2O + \text{Energy}$$

It is recognized, of course, that many intermediate steps are involved in this over-all reaction. Also important side reactions are occurring simultaneously which concern elements other than carbon and hydrogen. Neither of these facts, however, detract from the importance of this basic reaction in accounting for most of the organic matter decomposition in the soil.

The breakdown of proteins. The plant proteins and related compounds yield other very important products upon decomposition, in addition to the carbon dioxide and water mentioned above. For example, they break

Table 6:1. An Outline Showing, in a General Way, the Changes That the Organic Compounds of Plant Tissue Undergo in the Soil. The Process is One of Enzymic Digestion Which Results in the Synthesis of Humus, the Release of Energy, and the Formation of Simple Products.

I. Compounds Characteristic of Fresh Plant Tissue	
Decomposed with difficulty	*Decomposed easily*
Lignin	Cellulose
Oils	Starches
Fats	Sugars
Resins, etc.	Proteins, etc.
II. Complex Intermediate Products of Decay	
Resistant compounds	*Decomposition compounds*
Resins	Amino acids
Waxes	Amides
Oils and fats	Alcohols
Lignin, etc.	Aldehydes, etc.
III. Products of Soil-decomposition Processes	
Resistant complex	*Simple end products*
Humus—a colloidal complex in which the lignoproteinate is considered especially important	Carbon dioxide and water
	Nitrates
	Sulfates
	Phosphates
	Ca compounds, etc.

down into amides and amino acids [4] of various kinds, the rate depending on conditions. Bacteria, fungi, actinomycetes, and other soil organisms, both plant and animal, engage in the transformations, appropriating some of the nitrogen for their own use as the digestion proceeds.

Some of the protein, however, may combine with lignin and other resistant compounds and become a part of the soil humus. It is thus protected, at least for a time, from enzymic decomposition. Once amino acids are formed, they may be hydrolyzed readily to carbon dioxide, ammonium compounds, and other products. By the process of nitrification ammonium may be changed to nitrates, the form in which higher plants take up a large proportion of their nitrogen.

[4] Amino acids are produced by replacing one of the alkyl hydrogens with NH_2. Acetic acid (CH_3COOH) thereby becomes aminoacetic acid or glycocoll (CH_2NH_2-$COOH$). Amides or acid amides are formed from organic acids by replacing the hydroxyl of the carboxyl group with NH_2. Acetic acid (CH_3COOH) thus becomes acetamide (CH_3CONH_2).

Protein simplification probably progresses as follows:

Proteins → Proteoses → Peptones ↗ Amino acids ↘ / ↘ Acid amides ↙ ammonium compounds

An example of organic decay. Now let us view the process of organic decay in cyclic sequence. (See Fig. 6:2.) First assume a situation where no readily decomposable materials are present in a soil. As a result, microbial activity has sunk to a minimum and living soil organisms are much reduced in numbers. Now, under favorable conditions, let us introduce an abundance of fresh, decomposable tissue. A tremendous change immediately occurs. In the presence of compounds which furnish readily available energy and nutrients, the multiplication of soil microorganisms suddenly increases many fold. Microbial activity is soon at its peak, as is shown by the rapid liberation of energy and the tremendous evolution of carbon dioxide. That great group of general-purpose decay organisms, bacteria, fungi and actinomycetes, is soon fully active, and decomposition, as well as synthesis, goes on apace. (See Fig. 6:2.)

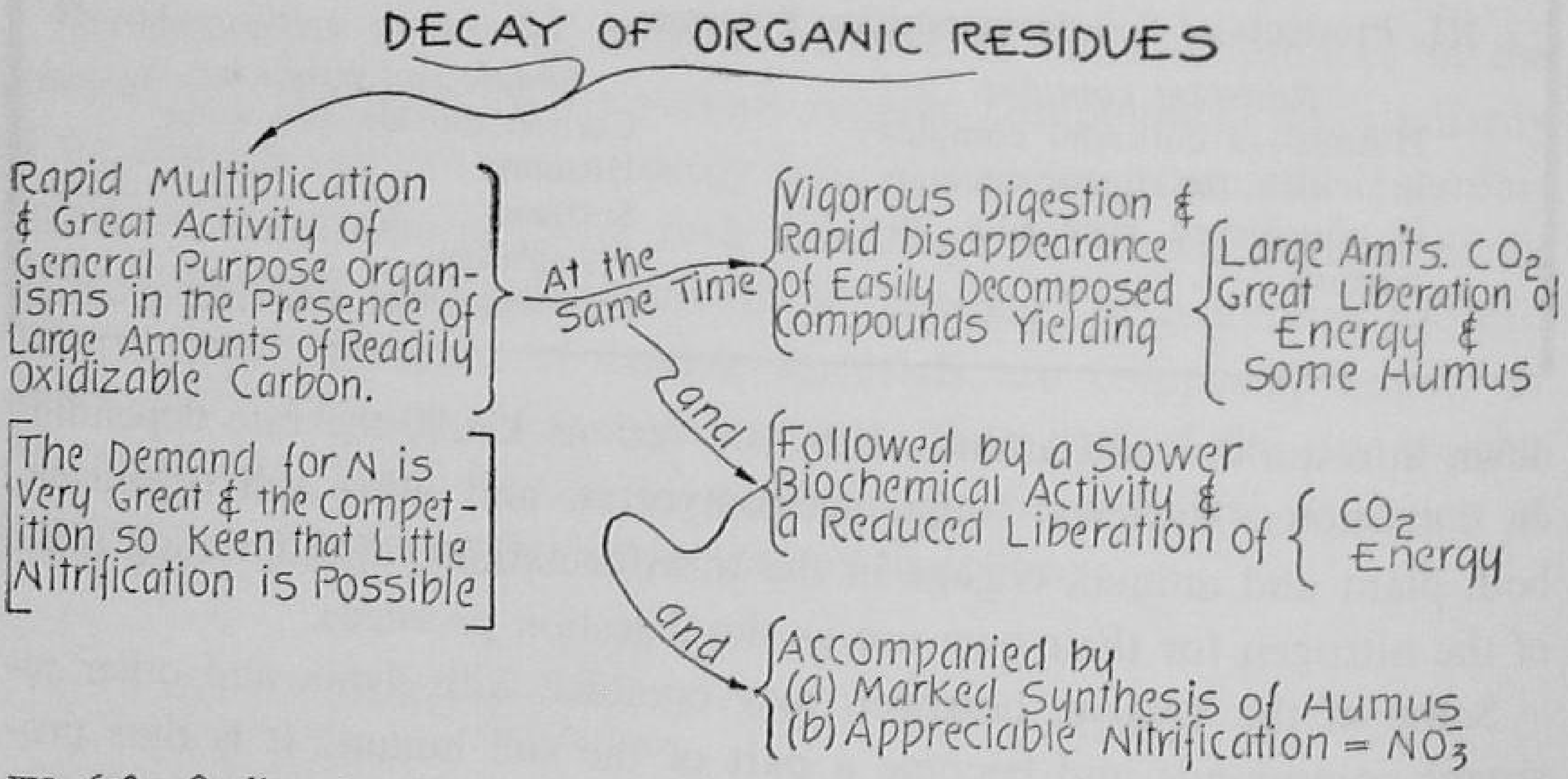

FIG. 6:2. *Outline showing the bio-chemical trend as organic residues undergo microbial digestion in the soil. Note the intense microbial competition that occurs, especially during the early stages of decomposition. This is accompanied by a copious loss of carbon as CO_2, and a great liberation of energy. Only when humification nears completion can the nitrifiers function vigorously and nitrate nitrogen appear in the soil.*

The soil organic matter at this stage contains a great variety of substances—intermediate products of all kinds, ranging from the more stable bodies such as lignins, to microbial cells, both living and dead. Indeed, the microbial tissue may even at times account for as much as one-half of the organic fraction of a soil.[5] These dead organisms are soon subject to decay,

[5] See Norman, A. G., "I. Problems in the Chemistry of Soil Organic Matter," *Proc. Soil Sci. Soc. Amer.*, 7: 7–15, 1942.

the compounds present being attacked by the living microbes. The process is accompanied, of course, by the copious evolution of carbon dioxide.

Finally, as the readily available energy is used up and food supplies diminish, microbial activity gradually lessens, and the general-purpose soil organisms sink back again into comparative quiescence. This is associated with a more or less abundance of simple products, such as nitrates and sulfates. The organic matter that now remains is a dark incoherent and heterogeneous colloidal mass and is usually referred to as *humus*. In short, we are back again to the condition first postulated after a complex cycle of decay, representative of the biochemical pulsations to which the soil is subjected.

It is well to emphasize that the decomposition of the original organic tissue of the soil and of the concurrent microbial tissue and their products is nothing more than a process of enzymic digestion. It is just as truly a digestion as though the plant materials entered the stomach of a domestic animal. The products of these enzymic activities, although numerous and tremendously varied, may be listed for convenience of discussion under three heads: (1) energy appropriated by the microorganisms or liberated as heat, (2) simple end products, and (3) humus. They will be considered in order.

6:4. THE ENERGY OF THE SOIL ORGANIC MATTER AND ITS TRANSFER [6]

The microorganisms of the soil, as they grow and multiply, must not only have substance for their tissue synthesis but energy as well. For most of the microorganisms,[7] both of these are obtained from the soil organic matter. All manner of compounds are utilized as energy sources, some freely, others slowly and indifferently.

Potential energy in organic matter. As might be expected, organic matter contains considerable potential energy, a large proportion of which is readily transferable to other latent forms or is liberated as heat. Plant tissue, such as that entering the soil, has a heat value in the neighborhood of 4 or 5 kilocalories to the gram of air-dry substance. The application of 10 tons

[6] For a discussion of these phases, see Waksman, S. A., *Principles of Soil Microbiology*, The Williams and Wilkins Company, Baltimore, 1932; and Buchanan, R. E., and E. I. Fulmer, *Physiology and Biochemistry of Bacteria*, The Williams and Wilkins Company, Baltimore, 1928.

[7] Autotrophic bacteria such as the nitrifiers and sulfur oxidizers are good examples of exceptions to this as their carbon comes mostly from carbon dioxide and their energy largely from the oxidation of inorganic substances.

of farm manure, for example, containing 5,000 pounds of dry matter, would mean an addition in round numbers of 9,000,000 to 11,000,000 kilocalories of latent energy. A soil containing 4 per cent of organic matter possesses about 80,000 pounds of dry organic substance to the acre-furrow-slice (2,000,000 pounds). This amount of organic residue possibly carries from 150,000,000 to 180,000,000 kilocalories of potential energy, equivalent in heat value perhaps to 20 to 25 tons of anthracite coal.

Of this large amount of energy carried by the soil organic matter, only a part is used by soil organisms. The remainder is left in the residues or is dissipated as heat. This heat loss represents a large and continual removal of energy from the soil. The evolution of carbon dioxide not only is a rough measure of this but also is an indication in general of the rate of the disappearance of the soil organic matter itself.

Rate of energy loss from soils. A rather interesting phase of the subject is the rate at which energy is dissipated from soils. Certain estimates made at the Rothamsted Experiment Station,[8] England, on two plats of the Broadbalk field, are rather suggestive in this respect. It was calculated that 1 million kilocalories an acre were lost annually from the untreated low producing soil, while about 15 million kilocalories were dissipated from the more productive soil receiving liberal supplies of farm manure. The magnitude of such loss is surprising even for the poorer plat.

Let us assume, as already suggested, that the average soil contains 150 million kilocalories of energy to the acre and that the annual dissipation is 10 million kilocalories. Thus, an amount equivalent to one-fifteenth of the total would be the yearly loss, a surprisingly rapid turnover of the organic matter. Such figures, estimates though they are, emphasize the amount of food necessary for the support of the soil organisms. They also show the difficulty that is usually encountered in maintaining a suitable amount of active organic matter in arable soils.

6:5. THE SIMPLE PRODUCTS OF ORGANIC MATTER DECOMPOSITION

As the enzymic changes of the soil organic matter proceed and humus is gradually built up, simple products begin to manifest themselves. Some of these, especially carbon dioxide and water, appear immediately. Others, such as nitrate nitrogen, accumulate only after the peak of the vigorous

[8] Russell, E. J., and E. W. Russell, *Soil Conditions and Plant Growth,* Longmans, Green and Company, London, 1950, p. 194.

decomposition is over and the general-purpose decay organisms have diminished in numbers. Since these simple end products, if not used by higher plants or microorganisms, are readily lost, they soon sink to a minimum, unless fresh tissue is added at frequent intervals.

The more common simple products that result from the activity of the soil microorganisms may be listed as follows:

Carbon	CO_2, $CO_3^{=}$, HCO_3^-, CH_4, elemental carbon
Nitrogen	NH_4^+, NO_2^-, NO_3^-, elemental nitrogen
Sulfur	S, H_2S, $SO_3^{=}$, $SO_4^{=}$, CS_2
Phosphorus	$H_2PO_4^-$, $HPO_4^{=}$ and $PO_4^{\equiv}$
Other simple	O_2, H_2, H_2O, H^+, OH^-, K^+, Ca^{++}, Mg^{++}, etc.

Some of the significant relationships of each of the five groups are presented in the following sections. They are considered in the order listed above.

6:6. SIMPLE PRODUCTS CARRYING CARBON—THE CARBON CYCLE

Carbon is the characteristic and omnipresent constituent of all organic matter. As a consequence, its movements during the microbial digestion of plant tissue are extremely significant. Most of the energy acquired by the fauna and flora within the soil comes from the oxidation of carbon and, as a result, its oxide is evolved continuously and in large amounts. The various changes that this element undergoes within and without the soil are collectively designated as the *carbon cycle* and are shown graphically in Fig. 6:3.

Release of CO_2. In all soil, higher plants furnish most of the various carbonaceous materials subject to microbial dissolution. As these compounds are digested, carbon dioxide is given off. This is the main soil source of this gas, although small amounts are excreted by plant roots and are brought down in rain water. The carbon dioxide of the soil, evolved both in summer and winter, ultimately escapes in large degree to the atmosphere, where it may again be used by plants. Thus the cycle is completed.

A lesser amount of carbon dioxide reacts in the soil, producing carbonic acid (H_2CO_3), and the carbonates and bicarbonates of calcium, potassium, magnesium, and other bases. These salts are readily soluble and may be lost in drainage or be used by higher plants. Thus, not only are Ca-, Mg-, and K-ions presented to the absorbing surfaces of microorganisms and

higher plants, but $CO_3^{=}$ and HCO_3^{-} ions are made available as well. Small amounts of carbon may enter plants in this way. (See note on page 42.) Most of the carbon present in higher plants, however, is acquired by photosynthesis.

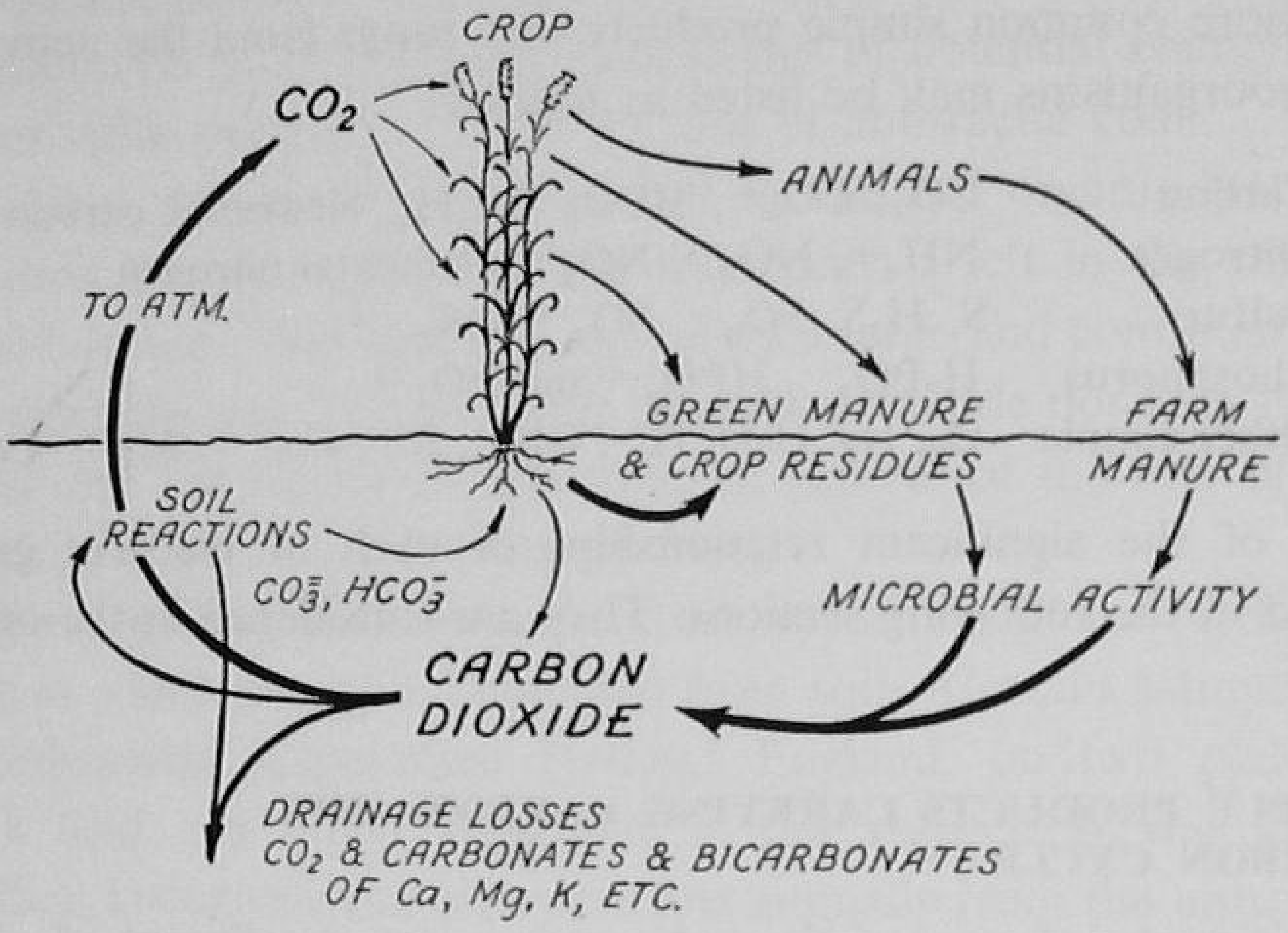

FIG. 6:3. *Diagrammatic representation of the transformations of carbon, commonly spoken of as the* carbon cycle. *Note the stress placed on carbon dioxide both within and without the soil.*

Other carbon products of decay. Besides carbon dioxide, carbonates, and bicarbonates, the simplification of organic matter results in other carbon products. Elemental carbon is found in soils to a certain extent, and while not especially important, its presence is significant. Under certain conditions, methane (CH_4) and carbon bisulfide (CS_2) may be produced in small amounts. But of all the simple carbon products, carbon dioxide is by far the most abundant.

It is now obvious that the carbon cycle is all inclusive since it involves not only the soil and its teeming fauna and flora, not only higher plants of every description, but also all animal life including man himself. Its failure to function properly would mean disaster to all. It is an energy cycle of such vital import that, with its many ramifications, it might properly be designated as the "Cycle of Life."

6:7. SIMPLE PRODUCTS CARRYING NITROGEN—AMMONIUM, NITRITE AND NITRATE IONS, AND ELEMENTAL NITROGEN

While carbon dioxide may result from the decomposition of any organic substance, ammonium salts are formed only when nitrogenous compounds

are involved. They are the first really simple nitrogen compounds that appear as the process of microbial digestion carries humification to completion. Proteins split up into amino acids and similar nitrogenous materials and these readily yield ammonium compounds by enzymic hydrolysis. These complex transformations are brought about by a large number of heterotrophic organisms—bacteria, fungi, and actinomycetes. The ammonium ion, as it appears in the soil solution commonly associates itself with carbonate or bicarbonate anions, so abundant in most soils. In this form, it is readily available, and many microorganisms and higher plants make use of this type of nitrogen freely.

Nitrification. If conditions are now favorable, ammonium ions are subject to ready oxidation, principally by two special-purpose organisms, the *nitrite* and the *nitrate* bacteria. These enzymic processes are affected by moisture conditions, temperature, aeration, and especially by available calcium. The transformations take place most readily when adequate lime is present. Also the activity of the general-purpose decay organisms must be at a minimum. Otherwise, due to competition, there would be no ammonium for the nitrifiers. In other words, humification must be fairly complete (see Fig. 6:2).

Nitrification may be shown simply and diagrammatically as follows:

$$2\ NH_4^+ + 3\ O_2 \xrightarrow[\text{Oxidation}]{\text{Enzymic}} 2\ NO_2^- + 2\ H_2O + 4\ H^+ + E$$

$$2\ NO_2^- + O_2 \xrightarrow[\text{Oxidation}]{\text{Enzymic}} 2\ NO_3^- + E$$

The organisms, autotrophic in this case, obtain energy by the transfer, and incidentally leave, as a by-product, nitrogen in the nitrate form. The second reaction usually follows so closely on the first as to prevent any appreciable accumulation of nitrites.[9] Nitrates are a form of nitrogen that many plants seem to need for their best growth. And it is in this combination that most of the loss of nitrogen in drainage occurs. Such removal is often so large as to seriously deplete soils of their nitrogen supply. (See page 247.)

The hydrogen ions formed in the first of the above reactions are of considerable practical importance. They show that nitrification tends to result in an increase in soil acidity. This effect is of even greater importance when

[9] Some biochemists hold that there are organisms that can accomplish individually the complete oxidation. In such a case probably no nitrites would be in evidence.

dealing with commercial fertilizers containing ammonium salts such as $(NH_4)_2SO_4$. Extra increments of lime are often added to counteract this acidifying effect.

Release of elemental nitrogen. One more end product awaits consideration—elemental nitrogen. Under certain conditions, the reduction of nitrates, nitrites, ammonium salts, and even of some of the simpler amino compounds takes place in soils, and free nitrogen may be evolved. This transfer is considered most likely to occur in poorly drained soils or in acid soils containing nitrites. The processes are very complicated and as yet are not fully understood. They apparently may be chemical as well as biochemical. In any case, however, the reduction is serious since elemental nitrogen ordinarily is extremely inert and is recombined with difficulty into compounds useful to higher plants. Some authorities feel that soils lose considerable nitrogen in this way. (See page 455 and ff.)

6:8. SIMPLE PRODUCTS CARRYING SULFUR—SULFITES, SULFATES, AND OTHER PRODUCTS

Many organic compounds, especially those of a nitrogenous nature, carry sulfur, which appears in simple forms as decay progresses. General-purpose heterotrophic types of organisms apparently are first involved, but ultimately the sulfur of the simplified by-products is subjected to oxidation by special bacteria, available calcium being of some aid in facilitating the transaction. Calcium is not as vital, however, as in the case of the nitrifiers since the special purpose, autotrophic sulfur organisms can carry on even when bases are deficient. The final transformation, which is carried to completion by the sulfur oxidizing organisms, may be shown diagrammatically as follows:

$$\underset{\text{Organic combinations}}{-[HS]} + 2\,O_2 \xrightarrow[\text{Oxidation}]{\text{Enzymic}} SO_4{}^{=} + H^+ + E$$

The organisms involved obtain energy by the transfer and leave the sulfur in the sulfate form. Unlike nitrification, which occurs in two distinct steps and requires two groups of organisms, sulfur oxidation apparently occurs, as indicated above, as one continuous reaction. Thus, the sulfur originally present in complicated combinations, emerges finally as a simple by-product and is available as the SO_4-ion, the form in which higher plants

absorb practically all of their sulfur. Considerable amounts of sulfate sulfur are lost in drainage, a phase that deserves some attention from the standpoint of fertility maintenance. (See page 247.)

6:9. ORGANIC PHOSPHORUS AND ITS MINERALIZATION

Not only is a large proportion of the soil phosphorus carried in organic combinations (see page 474) but under the influence of microorganisms such compounds are readily simplified. During this process the organic phosphorus is *mineralized,* appearing in the soil solution in inorganic combinations. The particular forms, as we already know (page 41), depend to a considerable degree upon soil pH. As the pH goes up, say from 5.5 to 7.5, the available phosphorus runs the gamut from H_2PO_4- to HPO_4- to PO_4-ions. All of these forms usually are readily available to higher plants. Since the small amount of phosphorus held in complex mineral combinations in soils usually is available slowly and with difficulty, the organic sources mentioned above become especially important.

It must not be assumed, however, that the maintenance of soil organic matter at normal or even high levels will solve the phosphorus problem. Far from it. Most field soils need liberal applications of superphosphate or other phosphatic fertilizers. Yet strangely enough, the economic use of such phosphorus depends to a considerable degree upon the organic transformation already cited. Since microorganisms utilize phosphorus freely, some of that added commercially quickly becomes a part of the soil organic matter. Thus, this phosphorus is held in an organic condition and is later mineralized by microbial activity.

6:10. OTHER SIMPLE PRODUCTS OF ORGANIC DISSOLUTION

A number of simple products resulting from the humification of organic residues need hardly more than mere enumeration. Water, elemental oxygen, and free hydrogen fall into this group. The development of H-ions, however, is quite a different matter as the following paragraph will affirm.

One feature of the carbon cycle that has been emphasized again and again is the copious production of carbon dioxide and the development, when in contact with water, of carbonic acid. Although very weak, carbonic acid develops enough active hydrogen to influence markedly the trend of numberless soil transactions. In fact, much of the active hydrogen of the soil solution and the adsorbed hydrogen of the colloidal complexes can be traced back to the influence of the carbon dioxide evolved from decom-

posing organic matter. Hence, the hydrogen-ion concentration of the soil solution fundamentally is an indirect manifestation of organic dissolution.

Because of its high adsorptive capacity, it is not surprising that soil organic matter usually carries considerable amounts of exchangeable potassium, calcium, magnesium, and other bases. Also, some of these same bases are present as integral constituents of the organic material itself. Hence, the addition of organic residues to soils and their subsequent decomposition therein cannot help but enhance the store of nutrient elements.

6:11. HUMUS—GENESIS AND DEFINITION

The formation of humus, although an exceedingly complicated biochemical process, may be described in general terms rather simply. Organic tissue, as it goes into the soil, is immediately and voraciously attacked, if conditions are favorable, by a host of different soil organisms. The easily decomposed compounds quickly succumb, first yielding intermediate substances and finally the simple, soluble products already enumerated.

Ligno-proteins. However, the oils, fats, resins, and especially the lignins [10] are more resistant and tend to persist, probably in a modified condition.[11] This modification is of especial concern, since it is thought by some to enable the lignin and other resistant materials to unite with proteins and allied nitrogenous compounds. An indefinite complex results that, for want of a better name, has been designated as a *ligno-proteinate* because of the supposed prominence of lignin in the synthetic process.[12]

Just how the lignins and similar substances are associated with the proteins is largely conjectural. Whether the union results from the synthetic activity of the microorganisms or is a direct chemical reaction or both, cannot as yet be asserted. The net result, however, is clean-cut. The product which results is persistent enough to influence soil character. At the same

[10] Lignin is a waxy or resinous material that impregnates the cell walls of plants as they increase in age. It is exceedingly complex, and varies with different plants and with different tissues of the same plant. The chemical formulae of the various lignins are in doubt. See Waksman, S. A., *Humus*, The Williams and Wilkins Company, Baltimore, 1938, pp. 99–101. Also, Norman, A. G., "Problems in the Chemistry of Soil Organic Matter," *Proc. Soil Sci. Soc. Amer.*, 7: 7–15, 1942.

[11] Gottlieb, S., and S. B. Hendricks, "Soil Organic Matter as Related to Newer Concepts of Lignin Chemistry," *Proc. Soil Sci. Soc. Amer.*, 10: 117–145, 1945.

[12] See Waksman, S. A., *Humus*, The Williams and Wilkins Company, Baltimore, 1938, Chap. 5.

A good discussion of soil organic matter and its various products will be found in *Soil Conditions and Plant Growth* by Russell, E. J., and E. W. Russell, Longmans, Green and Company, New York, 1950, Chap. 15.

time proteins are protected from immediate microbial dissolution. Consequently, the resultant mass (humus) carries considerable amounts of nitrogen, sulfur, phosphorus, and other nutrients.

Resistant microbial tissue. In addition to the altered lignin residues, apparently another group of compounds may be of considerable significance as constituents of humus.[13] These compounds, known as *polyuronides,* are thought to be synthesized by microorganisms, becoming a part of the microbial tissue. They are quite resistant to rapid decomposition when the organisms die. As a result, they may account for much of the residual organic matter present in soils. In some cases the quantity of the compounds containing uronic groups is quite high, uronic carbon making up as much as one-third of the total carbon. Thus, it is possible that dead microbial tissue may account for an appreciable fraction of the resistant organic matter (humus) present in soils.

Protein-clay combinations. In considering the stabilization of nitrogenous compounds in the soil, the possibility of a reaction between certain clays and proteinaceous substances should not be overlooked. Clays with expanding lattices, such as montmorillonite, seem to have such a faculty, the proteins perhaps functioning as bases in satisfying the adsorption capacity of the inorganic colloids.[14] How important this is in the average soil it is difficult to say. Nevertheless, it suggests that intermixed with the ligno-proteins and the uronides there may be clay-proteins in greater or lesser amounts. Such a postulate serves as a further reminder of the complexity and heterogeneity of this group of substances that collectively we speak of as humus. It is not at all surprising, therefore, to find widely different types of humus in different soils and even considerable variations from horizon to horizon in the same soil.

Once the genesis of soil humus is understood, at least in principle, it is quite possible to state the over-all concept in a few words. Specifically, humus may be defined as a complex and rather resistant mixture of brown or dark brown amorphous and colloidal substances that develop synthetically as the original organic tissues suffer enzymic dissolution by the

[13] Norman, A. G., "Problems in the Chemistry of Soil Organic Matter," *Proc. Soil Sci. Soc. Amer.,* 7: 7–15, 1942. Also, Bremner, J. M., "A Review of Recent Work on Soil Organic Matter," Part I, *Jour. of Soil Science,* 2: 67–82, 1951.

[14] Ensminger, L. E., and J. E. Gieseking, "Resistance of Clay-adsorbed Proteins to Proteolytic Hydrolysis," *Soil Sci.,* 53: 205–209, 1942. See also Allison, F. E., M. S. Sherman, and L. A. Pinck, "Maintenance of Soil Organic Matter: I. Inorganic soil colloid as a factor in retention of carbon during formation of humus," *Soil Sci.,* 68: 463–478, 1949.

various soil organisms. It is a natural body and, though exceedingly variable and heterogeneous, it possesses properties that distinguish it sharply from the original parent tissues and from the simple products that develop during its synthesis. Its nature is considered in the next section.

6:12. HUMUS—NATURE AND CHARACTERISTICS AS COMPARED WITH SILICATE CLAY

Humus, as has already been emphasized, is highly colloidal but unlike its mineral counterpart in the soil, it is amorphous and not crystalline. Moreover, its surface exposure, its adsorption, and its catalysis are, comparatively, far in excess of those exhibited by any of the clays. For instance, the cation exchange capacity of silicate clays commonly ranges from 8 to 100 milliequivalents per 100 grams. Well-developed humus from mineral soils, in sharp contrast, may show a total adsorptive power of from 150 to 300. In general, the presence of 1 per cent of humus in a mineral soil under humid-temperate conditions means an exchange capacity of perhaps 2 milliequivalents per 100 grams of soil. The comparable figure for clays would range from about 0.1 to 1.0, perhaps 0.5 being an average value.[15]

In respect to adsorbed water, the contrast is of the same order. The fully synthesized humus of a mineral soil will adsorb from a saturated atmosphere perhaps 80 or 90 per cent of water. Clay, on the other hand, may be able to thus acquire possibly only 15 or 20 per cent. The significance of these figures in respect to soil properties is obvious.

Physical properties. The low plasticity and cohesion of humus is a significant practical feature. The maintenance of this constituent in heavy field soils cannot help but alleviate unfavorable structural characteristics induced by large quantities of clay. A small increase in humus has physical effects far in excess of its proportionate amount. This is due to a considerable extent to granulation which it on occasion so markedly encourages.

Another physical character that is of outstanding interest is the color imparted to soils by humus. It is well to note definitely that the development of a black pigment in humus varies with climate.[16] In chernozem soils, occurring in northern semi-arid regions with an annual rainfall around

[15] Note that on the basis of the average figures quoted it should be possible to calculate in a rough way the cation exchange capacity of a whole soil providing its percentages of clay and organic matter are known. See note at bottom of page 110.

[16] Gillam, W. S., "The Geographical Distribution of Soil Black Pigment," *Jour. Amer. Soc. Agron.*, 31: 371–387, 1939.

20 inches, the pigment is very dark and abundant. The alternation of cold winters and hot, dry summers, with much of the rainfall coming in the spring, may, in part, account for this. The high lime content of the soil undoubtedly is a factor also. In humid-temperate zones, the pigmentation is less intense, while the least coloration is found in the humus of the tropics and semi-tropics. Color thus in a very general way is an expression of climate. This is a point well worth remembering as it indicates that organic pigmentation cannot be used satisfactorily as a comparative measure of the amount of organic matter present in soils.

Colloidal constitution. Soil humus, as a colloidal complex, is organized in much the same way as clay. (See page 96.) The ligno-proteinates, the polyuronides, the clay-proteins, and no doubt other constituents as well, function as complex micelles. Under ordinary conditions, these carry innumerable negative charges. But instead of being made up principally of Si, O, Al, and Fe, as are the silicate crystals, the humic micelles are composed of C, H, O, N, S, P, and other elements.

The humic micelles, like the lamellar particles of clay, exhibit the double-layer phenomenon and carry a swarm of adsorbed cations in exactly the same way. The same exchangeable cations (Ca^{++}, H^{+}, Mg^{++}, K^{+}, Na^{+}, etc.) are found in the outer layers, and cation-exchange properties of a markedly higher order occur. An understanding of the general organization of clay supplies a basis for a conception of the colloidal setup and chemical functioning of humus, especially in respect to cationic exchange phenomena. For this reason, humus, colloidally, may be represented by the same structural formula used for clay namely—

$$\begin{matrix} Ca \\ H \\ B \end{matrix} \boxed{\text{Micelle}}$$

and the same reactions will serve to illustrate cation exchange in both. (See page 108.) B represents all bases other than Ca.

Effect of humus on nutrient availability. There is one particular characteristic of humus that merits attention—the capacity of this colloid to increase the availability of certain nutrient bases, such as calcium, potassium, and magnesium. It seems that an H-humus, as is the case with an H-clay, acts much like an ordinary acid and can react with soil minerals in such a way as to extract their bases.[17] This is important, but more important still is the unusual capacity of an acid humus to effect such a

[17] The capacity of clayey acids to effect the dissolution of soil minerals, liberate nutrient bases, and hasten the development of more clay is considered on page 300.

transfer. This is because the organic acid is comparatively strong. Once the exchange is made, the bases so affected are held in a loosely adsorbed condition and, hence, are easily available to higher plants.

This capacity to mobilize nutrients is rated as one of the outstanding characteristics of acid humic colloids functioning in mineral soils.[18] The following generalized illustration is offered:

$$\underset{\text{microcline}}{KAlSi_3O_8} + H\boxed{\text{Humus}} \longrightarrow \underset{\text{acid silicate}}{HAlSi_3O_8} + \underset{\text{adsorbed K}}{K\boxed{\text{Humus}}}$$

Microcline is used as an example of the various soil minerals so affected, the potassium of which is changed from a molecular to an adsorbed status in which condition it is rated as rather readily available to higher plants.

Humus-clay complex in soils. In representing all the colloidal matter of a mineral soil by the general formula, $\begin{matrix}Ca\\H\\B\end{matrix}\boxed{\text{Micelle}}$, it must always be remembered that one is dealing with a heterogeneous mixture of many very different groups, each within itself remarkably diversified. The clayey nucleus, crystalline and lamellar, is markedly stable under ordinary conditions and is active mainly in respect to cation exchange. The organic micelle, on the other hand, amorphous and of no definite form, is susceptible to microorganic attack and hence has a twofold activity—cation exchange and a marked energy liberation. These contrasting details are just as important practically as the colloidal similarities already noted.

6:13. DIRECT INFLUENCE OF ORGANIC COMPOUNDS ON HIGHER PLANTS

One of the early beliefs in regard to plant nutrition was that organic matter, as such, is directly absorbed by higher plants. This opinion, afterwards, was definitely discarded. Later Hutchinson and Miller,[19] as well as other investigators, carefully studied the question of the assimilation of nitrogenous organic compounds by higher plants. The results, in general,

[18] Albrecht, William A., "Soil Organic Matter and Ion Availability for Plants," *Soil Sci.*, 51: 487–494, 1941.

[19] Hutchinson, H. B., and N. H. J. Miller, "The Direct Assimilation of Inorganic and Organic Forms of Nitrogen by Higher Plants," *Jour. Agr. Sci.*, 4, Part 3: 282–302, 1912.

Also, Schreiner, O., and J. J. Skinner, *Nitrogenous Soil Constituents and Their Bearing upon Soil Fertility*, Bul. 87, Bureau of Soils, U. S. Dept. of Agriculture, 1912.

indicate that certain of these can be absorbed by higher plants, often rather readily. But that such substances ordinarily do not satisfy their need for nitrogen is indicated by the ready response that most plants make to an application of nitrates.

Viewed in the light of such findings, it may be concluded that the soil organic matter may, to some extent, serve as a direct source of plant nutrients. As such it provides not only nitrogen and sulfur but also carbon, oxygen, and hydrogen, elements usually considered as coming from air and water. However, even under the most favorable conditions, such intakes undoubtedly are too small to be of practical significance from the nutrient standpoint.

However, the beneficial effects sometimes noted of an exceedingly small absorption of organic compounds might be accounted for by postulating the presence of growth-promoting substances. In fact, it is quite possible that vitamin-like compounds are developed as organic decay progresses in soils. If this be the case, the direct effect of humic substances upon higher plants might be much more important than hitherto has been suspected. Undoubtedly, many hormones and vitamins are carried by the soil humus and may at times greatly stimulate both higher plants and microorganisms.

On the other hand, some soil organic compounds no doubt may be harmful.[20] As an example, dihydroxystearic acid may be mentioned, as this was one of the first to be so studied. This compound was isolated from soil and identified in the United States Department of Agriculture and is very toxic to higher plants. Other compounds of a harmful nature were also isolated by the same investigators.

While twenty soils, out of a group of sixty taken in eleven states, were found to contain dihydroxystearic acid, this does not necessarily mean that this or similar injurious compounds are serious detrimental factors. It is very probable that such compounds are merely products of unfavorable soil conditions. And when such conditions are righted, the so-called toxic matter disappears. Good drainage and tillage, lime, and fertilizers are so efficacious in restoring normality that organic toxicity need never be feared in soils rationally managed.[21]

[20] Schreiner, O., and E. C. Shorey, *The Isolation of Harmful Organic Substances from Soils,* Bul. 53, Bureau of Soils, U. S. Dept. of Agriculture, 1909.

Schreiner, O., and J. J. Skinner, *Nitrogenous Soil Constituents and Their Bearing upon Soil Fertility,* Bul. 87, Bureau of Soils, U. S. Dept. of Agriculture, 1912.

[21] Davidson, J. D., "A Comparative Study of the Effects of Cumarin and Vanillin on Wheat Grown in Soil, Sand, and Water Culture," *Jour. Amer. Soc. Agron,* 7: 145–158, 1915.

6:14. CARBON-NITROGEN RATIO [22]

Attention has been called several times to the close relationship that exists between the organic matter and nitrogen contents of soils. Since carbon makes up a large and rather definite proportion of this organic matter, it is not surprising that the *carbon to nitrogen* ratio of soils is fairly constant. The importance of this fact in controlling the available nitrogen, total organic matter and the rate of organic decay should unfold as we consider the subject further.

The ratio of carbon to nitrogen in the organic matter of the furrow-slice of arable soils commonly ranges from 8:1 to 15:1, the median being between 10 and 12 to 1.[23] In a given climatic region, little variation is found in this ratio, at least in similarly managed soils. The variations which do occur seem to be correlated in a general way with climatic conditions, especially temperature and the amount and distribution of rainfall. For instance, it is rather well established that the carbon-nitrogen ratio tends to be lower in soils of arid regions than in those of humid regions when temperatures are comparable. It is also lower in warmer regions than in cooler ones, providing the rainfalls are of about the same magnitude. Also the ratio is narrower for subsoils, in general, than for the corresponding surface layers.[24]

Before discussing reasons for this relative constancy of the C:N ratio

[22] A few of the important articles dealing with the carbon-nitrogen ratio are cited below:

Holtz, H. F., and S. C. Vandecaveye, "Organic Residues and Nitrogen Fertilizers in Relation to the Productivity and Humus Content of Palouse Silt Loam," *Soil Sci.*, 45: 143–163, 1938.

Fowler, R. H., and L. C. Wheeting, "Nature of Organic Matter in Western Washington Prairie Soils as Influenced by Differences in Rainfall," *Jour. Amer. Soc. Agron.*, 33: 13–23, 1941.

Pinck, L. A., F. E. Allison, and V. L. Gaddy, "The Effect of Green Manure Crops of Varying Carbon-Nitrogen Ratios upon Nitrogen Availability and Soil Organic Matter Content," *Jour. Amer. Soc. Agron.*, 40: 237–247, 1948.

Dodge, D. A., and H. E. Jones, "The Effect of Long-Time Fertility Treatments on the Nitrogen and Carbon Content of a Prairie Soil," *Jour. Amer. Soc. Agron.*, 40: 778–785, 1948.

[23] See Anderson, M. S., and H. G. Byers, "The Carbon-Nitrogen Ratio in Relation to Soil Classification," *Soil Sci.*, 38: 121–138, 1934.

Also consult articles cited at bottom of page 000.

[24] See Jenny, H., *A Study on the Influence of Climate upon the Nitrogen and Organic Matter Content of the Soil*, Research Bulletin 152, Missouri Agr. Exp. Sta., 1930. Also, Rost, C. O., *et al*, "Some Properties of the Black Prairie Soils of Minnesota," *Proc. Soil Sci. Soc. Amer.*, 8: 388–390, 1943.

in soils, let us consider briefly the ratio of these two elements in plant residues and microbial tissue. As one would expect, the ratio of carbon to nitrogen of plant material is variable, ranging from 20 or 30 to 1 for legumes and farm manure to as high as 90 to 1, or even more, in certain strawy residues. All gradations between these extremes are found. The carbon-nitrogen ratio of the bodies of microorganisms, on the other hand, is not only more constant but much narrower, ordinarily falling between 4:1 and 9:1. Bacterial tissue, in general, is somewhat richer in protein than that of fungi and consequently has a narrower ratio.

It can be seen, therefore, that most organic residues entering the soil carry large amounts of readily oxidizable carbon and comparatively small amounts of total nitrogen—that is, their carbon-nitrogen ratio is wide. In the presence of such easily acquired energy there invariably occurs, if conditions are favorable, a rapid multiplication of the general-purpose, heterotrophic, decay organisms—bacteria, fungi and actinomycetes—and the copious evolution of carbon dioxide. This means a rapid loss of carbon. (See Fig. 6:2.)

The nitrogen, on the other hand, is largely conserved at this stage due to the microbial demand for this element as new cells develop and protoplasmic synthesis takes place. As a consequence, most of the nitrogen is retained in the soil by the heterotrophic flora while carbon is lost as carbon dioxide. As a result, the carbon-nitrogen ratio of necessity becomes progressively narrower as humification progresses.

Reason for C:N constancy. It is now possible to raise the question as to why the carbon-nitrogen ratio in any particular soil sinks to a certain level and remains more or less constant. Let us assume that an average residue, having a C:N ratio of 40 to 1 is added to a soil. As decay occurs, carbon dioxide is evolved while nitrogen is held in the microbial tissue. The carbon-nitrogen ratio steadily becomes narrower as the amount of easily available carbon decreases. Consequently, the activities of the general-purpose heterotrophic organisms are progressively curtailed. The microbial demand for nitrogen, therefore, markedly diminishes and, as a result, by-product ammonium begins to appear. Nitrification may now take place, if other conditions are favorable, and nitrate nitrogen, which hitherto has been absent, or at least very low, becomes evident. This form of nitrogen is subject to loss in drainage and also may be readily removed from the soil, together with the ammonium forms, by higher plants.

As decomposition processes continue, both carbon and nitrogen are now subject to loss. It is only a question of time until their percentage rate of disappearance from the soil becomes approximately the same, that is, the percentage of the total nitrogen being removed equals the percentage of the total carbon being lost. At this point the carbon-nitrogen ratio, whatever it happens to be, becomes more or less constant, always being somewhat greater than the ratios that characterize microbial tissue. As already stated, the carbon-nitrogen ratio in humid temperate region soils, especially if under cultivation, usually stabilizes in the neighborhood of 10 or 12 to 1.

6:15. THE SIGNIFICANCE OF THE CARBON-NITROGEN RATIO [25]

The carbon-nitrogen ratio in soil organic matter is an important factor in a number of ways, the two most significant of which are as follows: (1) Competition for available nitrogen results when residues having a high C:N ratio are added to soils. (2) Due to the constancy of this ratio in soils the maintenance of carbon, and hence soil organic matter, is dependent to no small degree on the soil nitrogen level. Let us consider these two factors in order starting with a practical example of the influence of highly carbonaceous material on the availability of nitrogen.

A practical example. Suppose that we are dealing with a representative cultivated soil in a condition favoring vigorous nitrification. Nitrates are present in relatively large amounts and, of course, the C:N ratio is narrow. The general-purpose decay organisms are at a low level of activity and CO_2 production is at a minimum. (See Fig. 6:4.)

Now suppose large quantities of organic residues with a wide C:N ratio (say 50:1) are incorporated in this soil under conditions supporting vigorous dissolution and digestion. A change quickly occurs. The heterotrophic flora—bacteria, fungi, and actinomycetes—becomes increasingly active and multiplies rapidly, yielding CO_2 in large quantities. Under these conditions, nitrate nitrogen practically disappears from the soil due to the insistent microbial demand for this element to build their tissues. And for the time being little or no nitrogen, even ammoniacal, is in a form available to higher plants.

This condition persists until humification nears completion, at which

[25] See Hutchings, I. J., and T. L. Martin, "Influence of the Carbon-Nitrogen Ratios of Organic Matter on Rate of Decomposition in the Soil," *Jour. Amer. Soc. Agron.*, 26: 333–341, 1934.

Also see Waksman, S. A., and I. J. Hutchings, "The Role of Plant Constituents in the Preservation of Nitrogen in the Soil," *Soil Sci.*, 40: 487–497, 1935.

time the activities of the decay organisms gradually subside due to a lack of easily oxidizable carbon. Their numbers decrease, CO_2 formation drops off, nitrogen ceases to be at a premium and nitrification can proceed. Nitrates again appear in quantity and the original conditions again prevail except, for the time being, the soil is somewhat richer both in nitrogen and humus. The sequence of events, an important phase of the carbon cycle, is diagrammatically represented in Fig. 6:4. Study it carefully.

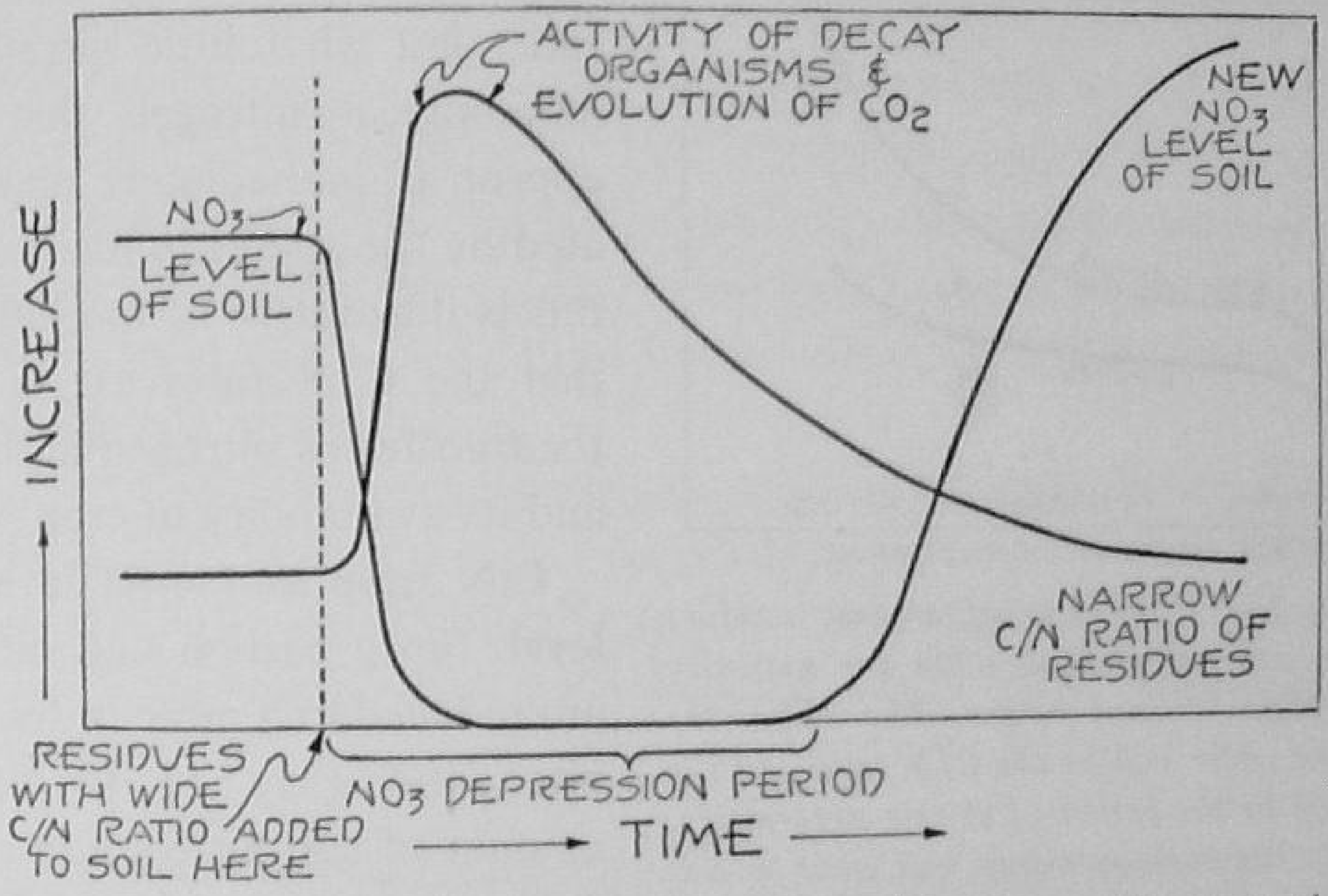

FIG. 6:4. *Diagram showing the cyclical relationship between the stage of decay of organic residues and the presence of nitrate nitrogen in soil. So long as the C/N ratio is wide, the general purpose decay organisms are dominant and the nitrifiers are more or less inactive. During the period of nitrate depression that results, higher plants can obtain but little nitrogen from the soil. The length of this period will depend upon a number of factors of which the C/N ratio is of prime importance. This figure is another version of Fig. 6:2.*

Period of nitrate depression. The time interval of nitrate depression, the feature especially correlated with the C:N ratio, may be long or short depending on conditions. Rate of decay will lengthen or shorten the period as the case may be. And, of course, the greater the amount of residues applied the longer will nitrification be blocked. Also, the narrower the C:N ratio of the residues applied, the more rapidly, other conditions being equal, the cycle will run its course. Hence alfalfa and clover residues should interfere least with nitrification and yield their nitrogen more quickly than though oats or wheat straw was plowed under. Also mature residues,

whether legume or non-legume, have much higher C:N ratio than do younger succulent materials. (See Fig. 6:5.) These facts are of much practical significance and should be considered when organic residues are added to a soil.

Moreover, cultivation by hastening oxidation should encourage nitrification while a vigorous sod crop, such as blue grass, always maintains the soil in an almost nitrateless condition. This is because the root and top residues maintain a wide C:N ratio and what little nitrate and ammoniacal nitrogen that does appear is immediately appropriated by the sod crop itself. All of this is illustrative of the influence that the C:N ratio exerts upon the transfer of nitrogen in the soil and its availability to crop plants.

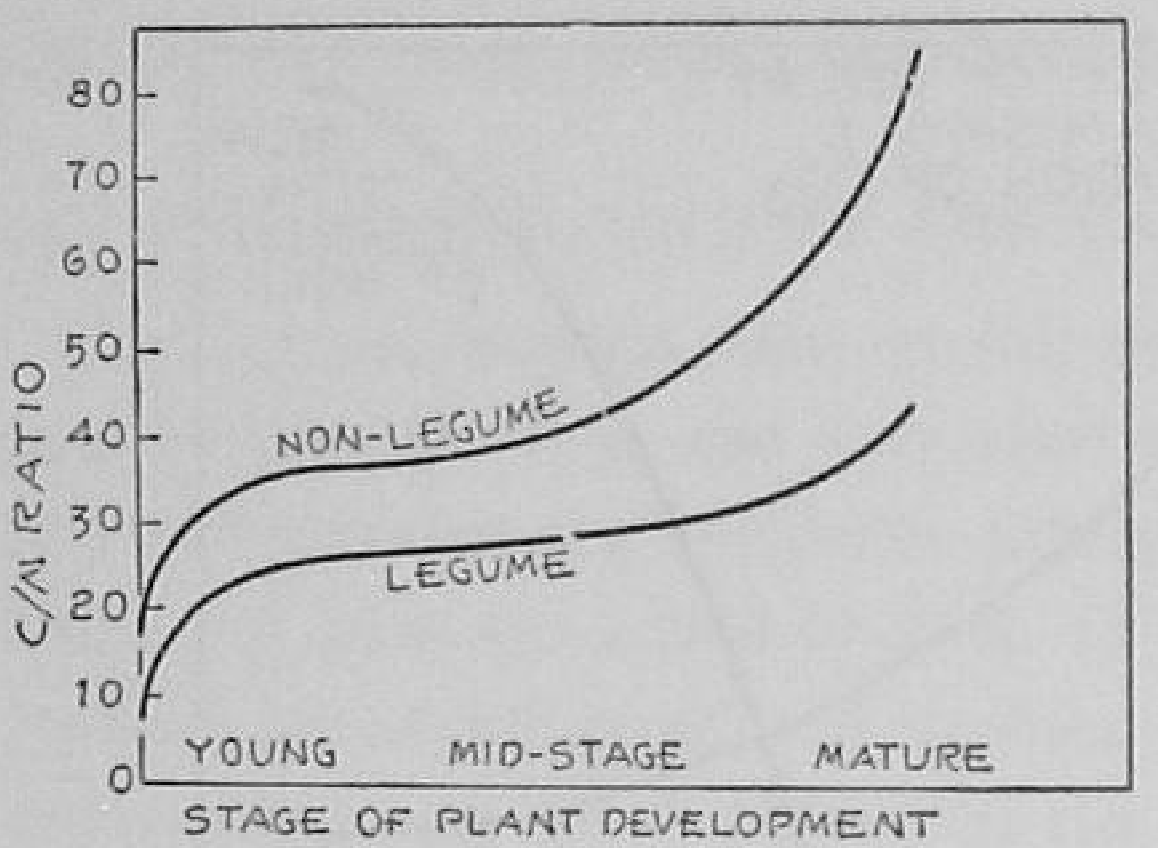

FIG. 6:5. *The C/N ratio of organic residues added to soil will depend upon the maturity of the plants turned under. The older the plants, the wider will be the C/N ratio and the longer will be the period of nitrate suppression. Obviously leguminous tissue will have a distinct advantage over non-legumes since the former will promote a more rapid organic turnover in soils.*

C:N ratio and organic matter level. Since carbon and nitrogen are reduced to a more or less definite ratio (say 11 to 1) the amount of soil nitrogen in reality determines the amount of organic carbon finally present when stabilization occurs. Thus, the greater the amount of nitrogen present in the original residue, the greater will be the possibility of an accumulation of organically combined carbon. And since a rather definite ratio (about 1:1.7) exists between the organic carbon and the soil humus, the amount of organic matter that can be maintained in any soil is largely contingent upon the amount of organic nitrogen present.[26]

To be sure that this relationship is clear the following illustrative calculation is offered. Suppose two lots of organic residues are taken, the dry matter of each weighing 10,000 pounds and each carrying 5,000 pounds of organic carbon. But lot No.1 contains only 100 pounds of total nitrogen while lot No.2 has 200 pounds. Their C:N ratios are, therefore, 50:1 and 25:1 respectively. Let us see which one, theoretically, will produce the

[26] The ratio between nitrogen and organic matter is thus rather constant. A value for the O.M./N ratio of 20/1 is commonly used for average soils. See page 171.

more humus when digested in the soil. Remember their original dry weights are equal.

For purposes of calculation assume that in both cases the humification is just completed at a C:N ratio of 10:1 and that all of the original nitrogen has been carried through the digestion without loss. Obviously in the first case the 100 pounds of nitrogen will have associated with it 1,000 pounds of carbon (100 × 10) and the loss of carbon during humification will be 4,000 pounds. In the second case the carbon conserved will be 2,000 pounds (200 × 10) and the digestion loss only 3,000 pounds. If the ratio between the organic carbon and the humus carrying it is of the order of 1:1.7, the theoretical yield of humus in the two cases will be approximately 1,700 and 3,400 pounds respectively. This fully substantiates the thesis that the higher the nitrogen content of the residues incorporated in the soil, the greater, other conditions being equal, should be the possibility of humus accumulation.

Practical deductions respecting the carbon-nitrogen ratio are thus clear-cut. Apparently the ratio is related not only to the availability of soil nitrogen but also to the maintenance of soil organic matter. In practical handling of cultivated soils both of these phases must receive due consideration.

6:16. AMOUNTS OF ORGANIC MATTER[27] AND NITROGEN IN SOILS

The amounts of organic matter in mineral soils vary so widely that it is difficult to present representative figures. Mineral surface soil, corresponding roughly to the furrow-slice, may contain from a trace to 15 or 20 per cent of organic matter. The average organic matter and nitrogen contents of large numbers of soils from different areas of the United States are shown in Table 6:2. One is immediately impressed by the relatively wide ranges in organic matter encountered in these soils, even in comparatively localized areas. Thus, the West Virginia soils have a range from 0.74 per cent to

[27] It is to be noted that no figures are offered as to the amount of humus present in mineral soils. This is partly due to the fact that no very satisfactory method is available for its determination. Moreover, soil samples usually are taken when humification is more or less complete. At that time the percentage of total organic matter is a fairly good measure of humus content.

Unfortunately there is no very satisfactory method of determining directly the exact quantity of total organic matter present in soil. The usual procedure is to find first the amount of organic carbon which can be done quite accurately. This figure multiplied by the factor 1.7 will give the approximate amount of organic matter present.

more than 15 per cent of organic matter. The several factors which may account for this wide variability as well as for the differences between averages in Table 6:2 will be considered in the next section.

It will be noted that the data in the table are for surface soils only. As might be expected, the organic matter contents of the subsoils are generally much lower. (See Fig. 6:6.) This is readily explained when we consider that most of the organic residues in both cultivated and virgin soils are incorporated in or deposited on the surface. This increases the possibility for organic matter accumulation in the upper layers.

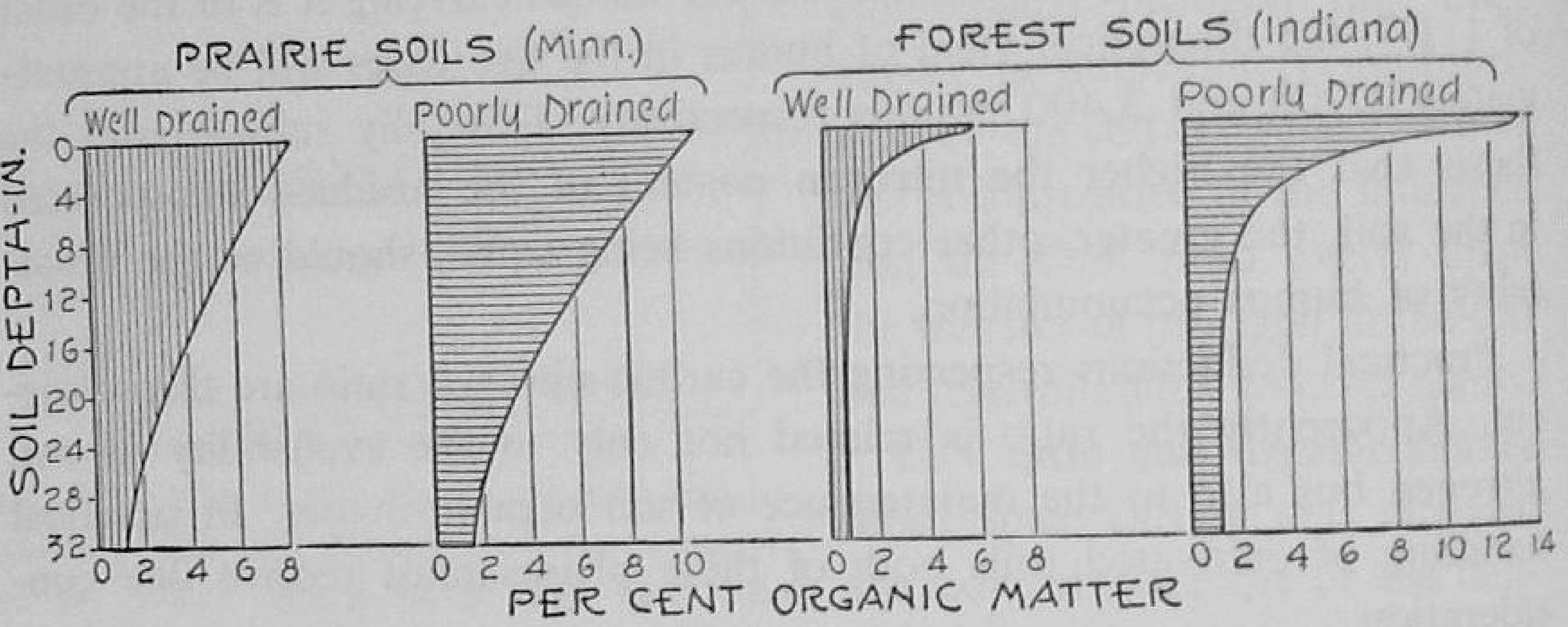

FIG. 6:6. *Diagrams showing the distribution of organic matter in four soil profiles.* Note that the prairie soils have a higher organic matter content in the profile as a whole compared to the corresponding soils developed under forest vegetation. Poor drainage results in a higher organic matter content, particularly in the surface horizon.*

The organic matter to nitrogen ratio. Before turning to the specific factors affecting the organic matter and nitrogen contents of soils, let us consider one more significant feature of the data in Table 6:2. In comparing the average organic matter and nitrogen contents of the soils listed one finds that there is about 20 times as much organic matter as nitrogen. This figure is fairly consistent as long as average data on a large number of soils are compared.

The explanation for the above constancy is obvious if we consider the information already presented concerning nitrogen, carbon and organic

* The forest soils are reported by R. A. Weaver, T. M. Bushnell, and G. D. Scarseth, "Correlative Studies of Indiana Soils: I. Some Physical and Chemical Characteristics of Seven Major Soil Types," *Proc. Soil Sci. Soc. Amer.*, 13:484–493, 1948.

The prairie soils are averages obtained from C. O. Rast, and F. J. Alway, "Minnesota Glacial Soil Studies: I. A Comparison of Soils on the Late Wisconsin and Iowan Drifts," *Soil Sci.*, 11:206, 1921.

Table 6:2. The Average Nitrogen and Organic Matter Contents of Mineral Surface Soils in Several Areas of the U.S. The Ranges Found for These Two Constituents Are Also Given.

Soils	% Organic Matter		% Nitrogen	
	Range	Ave.	Range	Ave.
240 West Va. soils [28]	0.74–15.1	2.88	.044–.54	.147
15 Penn. soils [29]	1.70– 9.9	3.60	——	——
117 Kansas soils [30]	0.11–3.62	3.38	.017–.27	.170
30 Nebraska soils [31]	2.43–5.29	3.83	.125–.25	.185
9 Minn. Prairie soils [32]	3.45–7.41	5.15	.170–.35	.266
21 Southern Great Plains soils [33]	1.16–2.16	1.55	.071–.14	.096
21 Utah soils [34]	1.54–4.93	2.69	.088–.26	.146

matter. It will be remembered that the C:N ratio of mineral soils is rather constant, and that the organic matter content is about 1.7 times as great as the carbon content. Thus, if a C:N ratio of 11.7 to 1 is assumed, the organic matter to nitrogen ratio is 11.7×1.7 or about 20:1. This figure is of considerable value in making rough calculations respecting these two constituents.[35]

6:17. VARIATIONS AND CORRELATIONS OF SOIL ORGANIC MATTER AND NITROGEN

In scanning the data presented in the preceding section, one cannot but be impressed by the variability in organic matter and nitrogen contents of

[28] Salter, R. M., and C. F. Wells, *Analyses of West Virginia Soils*, Bulletin 168, W. Va. Agr. Exp. Sta., 1918.

[29] Alderfer, R. B., and F. G. Merkle, "The Comparative Physical Constitution of Water Stable Granules and of the Original Soil," *Soil Sci.*, 53: 105–113, 1942.

[30] Swanson, C. O., *Chemical Analyses of Some Kansas Soils*, Kans. Agr. Exp. Sta., Bul. 199, 1914.

[31] Alway, F. J., and G. R. McDole, "The Loess Soils of the Nebraska Portion of the Transition Region: I. Hygroscopicity, Nitrogen and Organic Carbon," *Soil Sci.*, 1: 197–238, 1916.

[32] Rost, C. O., *et al.*, "Some Properties of the Black Prairie Soils of Minnesota," *Proc. Soil Sci. Soc. Amer.*, 8: 388–395, 1943.

[33] Daniel, Harley A., and Wright H. Langham, "Some Physical and Chemical Properties and the Kind of Organic Matter Affecting Color in Randall Clay and Upland Soils of the Southern Great Plains," *Soil Sci.*, 45: 369–383, 1938.

[34] Bracken, A. F., and J. E. Greaves, "Losses of Nitrogen and Organic Matter from Dry-farm Soils," *Soil Sci.*, 51: 1–15, 1941.

[35] It goes without saying that the percentage of organic matter in a single sample of soil, when calculated from the percentage of total nitrogen by the factor ($N \times 20$), is an extremely untrustworthy figure. But when the factor is applied to the average percentage of nitrogen in a large number of soils, it gives a comparatively accurate group figure, especially for arable soils.

representative mineral soils. Wide differences are evident, not only between soils of different physiographic provinces but also between closely contiguous areas in any particular locality. Heterogeneity seems to be the rule. This is expected by all pedologists. Let us consider the broader aspects first.

The influence of climate. Climatic condition,[36] especially *temperature* and *rainfall,* exert a dominant influence on the amounts of nitrogen and organic matter found in soils. As progress is made from a warmer to a cooler climate, especially in regions where the rainfalls are similar as to amount and distribution, the organic matter and nitrogen of soils tend to increase. At the same time, the C:N ratio widens somewhat. In general, the decomposition of organic matter is accelerated in warm climates while a lower loss is the rule in cool regions. Within belts of uniform moisture conditions and comparable vegetation, the average total organic matter and nitrogen increase from two to three times for each 10° C. fall in mean annual temperature.

The situation is well illustrated by conditions in the Mississippi Valley region. (See Fig. 6:7.) Here, the northern prairie soils and chernozems contain in general considerably greater amounts of total organic matter and nitrogen than those that lie to the southward. When the amount of original tissue yearly added to the soil is taken into consideration, the tropics, where plants grow so luxuriantly, afford an even better example of the influence of temperature on the rapidity of decay and disappearance of organic materials. In spite of this, however, many tropical surface soils are surprisingly high in organic matter.

Effective soil moisture also exerts a very positive control upon the accumulation of organic matter and nitrogen in soils as definite, in many respects, as that of temperature. In general, under comparable conditions, the nitrogen and organic matter increase as the effective moisture becomes greater. (See Fig. 6:7.) At the same time, the C:N ratio becomes wider. This is especially true for the grasslands. The explanation lies not only in the rapidity of microbial action and hence a more complete humification

[36] See Jenny, H., "Relation of Climatic Factors to the Amount of Nitrogen in Soils," *Jour. Amer. Soc. Agron.*, 20: 900–912, 1928; *A Study of the Influence of Climate upon the Nitrogen and Organic Matter Content of Soil*, Research Bulletin 152, Missouri Agr. Exp. Sta., 1930; and *Factors of Soil Formation*, McGraw-Hill Book Company, Inc., New York, 1941.

Also see Vanderford, H. B., and W. A. Albrecht, *The Development of Loessial Soils in Central United States as It Reflects Difference in Climate*, Research Bulletin 345, Missouri Agr. Exp. Sta., 1942.

in areas of moderate to low rainfall but also in the scantier vegetation of these regions. In arriving at the rainfall correlation such as advanced above, it must not be forgotten that the organic situation in any one soil is in large degree an expression of both temperature and precipitation plus other factors as well. Climatic influences never work singly.

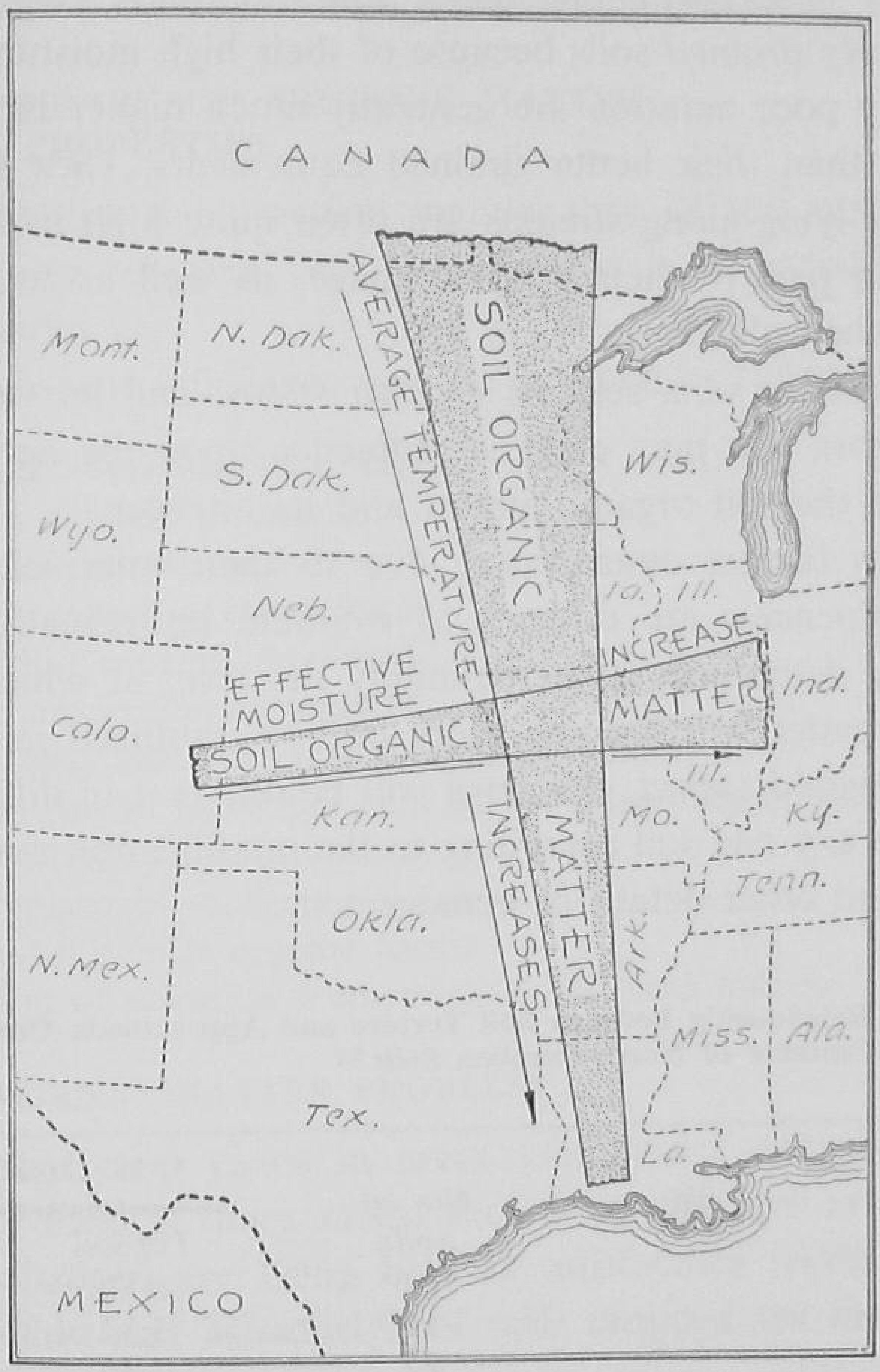

FIG. 6:7. *Map showing the influence of the average annual temperature and the effective moisture on the organic matter contents of grassland soils of the Midwest. Of course, the soils must be more or less comparable in all respects except for climatic differences.*

Note that the higher temperatures yield soils lower in organic matter. The effect of increasing moisture is exactly opposite, favoring a higher level of this constituent. These climatic influences affect forest soils in much the same way.

The effect of texture, drainage, and other factors. Besides the two broader aspects discussed above, there are numerous local relationships that should be mentioned. In the first place, the *texture* of the soil, other fac-

tors being constant, seems to influence the percentage of humus and nitrogen present. A sandy soil, for example, usually carries less organic matter and nitrogen than one of a heavier nature. (See Table 6:3.) This is probably due to the lower moisture content and to the more ready oxidation that occurs in the lighter soils. Also the natural addition of residues normally is less with the lighter soil.

Again, *poorly drained* soils because of their high moisture relations and their relatively poor aeration are generally much higher in organic matter and nitrogen than their better drained equivalents. (See Fig. 6:6.) For example, soils lying along streams are often quite high in organic matter. This is due in part to their poor drainage, as well as to the wash they receive from the uplands.

The *lime content* of a soil, its *erosion* status, and its *vegetative cover*, are other factors that may exert an influence upon the accumulation and the activity of the soil organic matter and its nitrogen.

The various factors enumerated, due to their interlocking and interdependent influences, are difficult to evaluate individually. Collectively, however, they determine rather definitely the level at which the nitrogen and organic matter will become more or less stabilized in any particular case. As one would expect, this level will be different in different soils and will change in any one soil according to the modification made in its vegetative cover and other details of management.

Table 6:3. The Relationship Between Soil Texture and Approximate Organic Matter Contents of a Number of North Carolina Soils [37]

Soil Type	*No. of Soils*	*% Organic Matter* Topsoil	*% Organic Matter* Subsoil
Cecil sands	15	0.80	0.50
Cecil clay loams	10	1.32	0.56
Cecil clays	27	1.46	0.64

Normally a very marked change occurs when a virgin soil, either forest or prairie, is placed under cultivation. New and usually lower levels of organic matter and nitrogen are gradually established as the soil seeks

[37] These figures were calculated by multiplying the % N by 20. The original data came from Williams, C. B., *et al.*, *Report on the Piedmont Soils particularly with reference to their nature, plant-food requirements and adaptability for different crops*, Bul. North Car. Dept. Agr., 36, No. 2, 1915.

equilibrium. It is not surprising, therefore, to find cultivated land much lower in organic matter and nitrogen, by perhaps 30 to 60 per cent, than its virgin equivalent. Such a drop is perfectly normal and is difficult to forestall. Hence in practice it is hardly worth while to attempt a maintenance much above certain percentages, providing good crops can be grown under these conditions. But more about that later.

6:18. INFLUENCE OF SOIL ORGANIC MATTER ON SOIL PROPERTIES

Before discussing the practical maintenance of soil organic matter, it might be well to rehearse very briefly what is expected from this all-important constituent.

The most obvious influences may be outlined as follows:

1. Effect on soil color—brown to black
2. Influence on physical properties
   a. Granulation encouraged
   b. Plasticity, cohesion, etc. reduced
   c. H_2O holding capacity increased
3. High cation adsorption capacity [38]
   a. Two to thirty times as great as mineral colloids
   b. Accounts for 30 to 90 per cent of the adsorbing power of mineral soils
4. Supply and availability of nutrients
   a. Easily replaceable cations present
   b. N, P, and S held in organic forms
   c. Extraction of elements from minerals by acid humus

6:19. THE ORGANIC MATTER PROBLEM

The fact that crop yields in areas long under cultivation have been maintained or even at times raised somewhat does not mean that organic matter and nitrogen are being held at satisfactory levels. In fact, comparisons in Ohio and Missouri [39] of soils cropped for long periods with

[38] First check the footnote calculation at bottom of page 110.
Then, if further information is desired, consult Bartlett, J. B., R. W. Ruble, and R. P. Thomas, "The Influence of Hydrogen Peroxide Treatments on the Exchange Capacity of Maryland Soils," *Soil Sci.*, 44: 123–138, 1937, and Olson, L. C., and R. H. Bray, "The Determination of the Organic Base-Exchange Capacity of Soils," *Soil Sci.*, 45: 483–496, 1938. Also see Rich, C. I., and S. S. Obenshain, "Effect of Certain Soil Treatments on the Cation Exchange Properties and Organic Matter Content of Dunmore Silt Loam," *Proc. Soil Sci. Soc. Amer.*, 8: 304–312, 1943.

[39] Salter, R. M., R. D. Lewis, and J. A. Slipher, *Our Heritage—the Soil*, Extension Bul. 175, Ohio Agr. Exp. Sta., 1941; and Klemme, A. W., and O. T. Coleman, *Evaluating Annual Changes in Soil Productivity*, Bul. 405, Missouri Agr. Exp. Sta., 1939.

their virgin equivalents indicate a reduction on the average of about 35 per cent in respect to their nitrogen. This would mean a more or less proportionate lowering in total organic matter.

That it is impossible in most cases to maintain the organic matter and nitrogen of our soils, whether forest or prairie, at their virgin levels is obvious. Nor is this necessary or even desirable. Yet a decline in organic matter content of 30 to 40 per cent is serious and should go no further. Such exploitation, if continued, may ultimately result in a definite decrease in crop yield. In practice it is not enough simply to bring to a halt this slow decline in the inherent capacity of soils to produce crops. It should be raised, not sharply or to any great degree, for this would be too expensive, but enough to insure a continuance of our present crop yields. Hence, the importance of the maintenance of soil organic matter above a certain level and with it a satisfactory nitrogen supply.

6:20. THE REGULATION OF SOIL ORGANIC MATTER

The preceding discussion has established two definite conclusions regarding the organic matter and nitrogen of soils, especially of those under cultivation. Both findings are of vital practical import. Firstly, the inherent capacity of soils to produce crops is closely and directly related to their organic matter and nitrogen contents. Secondly, a satisfactory level of these two constituents is difficult to maintain in the majority of farm soils. Because of this situation, methods of organic matter additions and upkeep should receive early consideration in all soil management programs.

For convenience, let us deal with the problem under four headings: (1) the sources of organic supplies, (2) soil conditions favoring the satisfactory decay and utilization of the added residues, (3) crop rotation in its relation to humus maintenance, and (4) the economy of organic matter upkeep. These phases will be considered in order.

Source of supply. Organic matter may be added to cultivated soils in a number of different ways. One, an artificial method, is the plowing under of crops when in an immature, succulent stage. This is called *green-manuring* and is a very satisfactory practice when it can be accommodated to the rotation. Such crops as rye, buckwheat, oats, peas, soybeans, vetch, as well as others lend themselves to this method of soil improvement. Not only do these crops help maintain the actual organic content of a soil, but in the case of legumes, at least a part of the nitrogen may be drawn from the air. This is a great advantage as such residues have a

comparatively narrow C:N ratio, decay rapidly, and yield more humus than do tissues with a smaller amount of nitrogen.

A second source of organic matter supply on many farms, especially in dairy sections, is *farm manure*. When applied at the usual rates, say 10 or 15 tons per acre during a five-year rotation, perhaps from 1,000 to 1,500 pounds of dry matter go into the soil as a yearly acre average. Such additions cannot but greatly aid in organic matter maintenance.

Moreover, farm manure is valuable because of the nitrogen that it carries which influences soil organic matter in two ways. As a nutrient it tends to increase crop yields and thus enhances the organic residues that the soil falls heir to. Also, this nitrogen through its associative control of organic carbon (see page 168) tends to stabilize the decay processes at a higher humus level. Hence, farm manure although of primary value as a nitrogen fertilizer is by no means unimportant in the struggle to maintain soil organic matter. In the same category with farm manure, but of much less concern, are *artificial farm manures* (page 537) and *composts*. The latter are employed mostly in the management of nursery, garden and greenhouse soils.

The third and, in general, the most important sources of organic residues, especially with arable soils, are the *current crops* themselves. Stubble, aftermath and especially root residues of various kinds, left in the soil to decay, make up the bulk of such contributions. Few farmers realize how much residual root systems aid in the conditioning of their soils. Without them the practical maintenance of the humus in most cases would be impossible.

In this connection it should also be remembered that the maintaining of high crop yields through proper *liming* and *fertilizer practices* may be just as effective as adding manure or other organic residues. (See Fig. 6:8.) Apparently in some cases organic matter can be maintained by simply raising bumper crops. Optimum yields usually mean more residues to return to the soil and certainly increases the amount of roots remaining after harvest.

Proper soil condition. In order that organic materials added to any soil may perform their normal functions, soil conditions, in general, should be of the best. This means careful and opportune tillage and cultivation. Proper drainage systems should be installed, if necessary, in order to promote satisfactory aeration and granulation. Lime should be added if basic materials are lacking, for it promotes bacterial activity as well as plant

growth. The addition of commercial fertilizers will often be physically advantageous. In any case increased crop growth should make possible a larger addition of organic matter, especially through crop residues and farm manures.

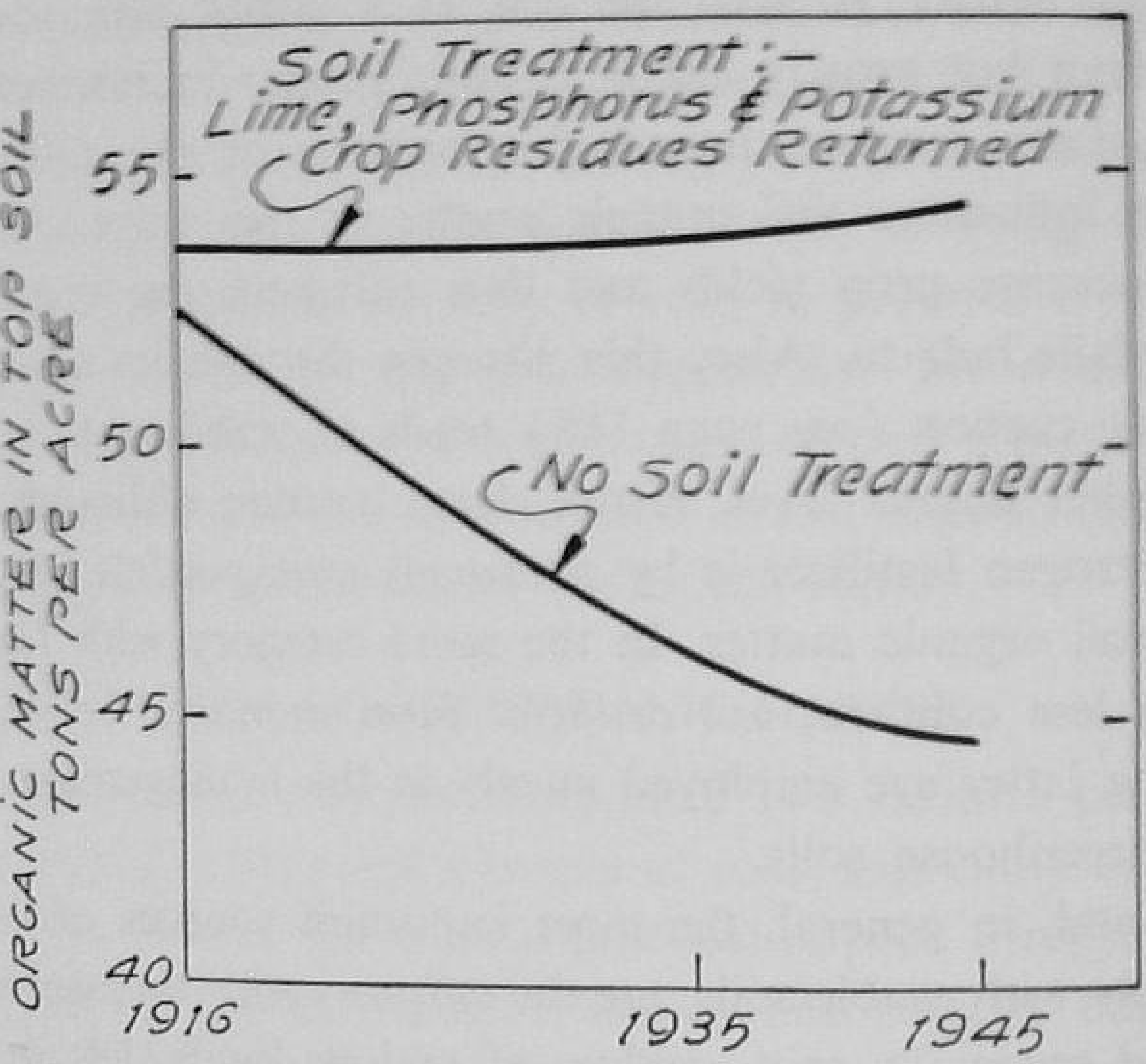

FIG. 6:8. *Diagram showing the influence of soil treatment upon the organic matter of an Illinois black soil (Bloomington series) over a period of 29 years. The rotation was corn—oats—wheat—clover. The organic matter was calculated (N X 20).*

The curves show two things: (1) the disastrous effect of farming this soil with no treatment and (2) the possibility of maintaining, or even increasing, the organic matter and nitrogen contents. After 29 years, the treated soil apparently was at a high level of fertility. (Data from Snider, H. J., "Soil Building with Legumes," *Ill. Agr. Exp. Sta. Bul.* 539, *553, 1950.)*

Crops and crop sequence. It has already been suggested that certain sod crops, such as meadow and pasture grasses and legumes, tend to facilitate humus accumulation. This is partly due to their liberal contributions of organic residues, the slow decay of these materials and their wide C:N ratios, kept so by continual root sloughage. This means that little nitrogen can appear in the soil in the nitrate form (page 167) and hence rather slight losses of this constituent will occur except when the crops are harvested. In the case of legumes this may be offset, at least in part, by nitrogen fixation. Since the amount of humus depends directly upon the amount of organic nitrogen (page 168) sod crops by their nitrogen

economy promote the highest possible yields of humus. Everyone knows that sod begets humus.

Cultivated crops, on the other hand, remove as much or even more nitrogen at harvest than do sod crops. Besides, tillage and other features of their management encourage an extremely rapid rate of decay and dissipation of organic matter. As a result the C:N ratio quickly becomes narrow thereby encouraging vigorous nitrification and a probable loss of nitrates in drainage. Thus, intertilled crops are associated with nitrogen depreciation instead of with economic stabilization, and with humus reduction instead of with humus accumulation. Small grains, such as oats and wheat, are in the same category—that is, they are humus wasters but to a lesser degree.

In practice, advantage is taken of the tendencies outlined above and crop sequences are so arranged as to offset humus depreciation with humus conservation and even appreciation. That much can be accomplished by the utilization of a suitable rotation, unaided by farm manure and commercial fertilizers is evidenced by the following data (Table 6:4) from Wooster, Ohio,[40] where unfertilized plots were cropped in various ways for a long period of time.

Table 6:4. Organic Matter and Nitrogen Contents of Unfertilized Soil Plots at Wooster, Ohio, After Being Cropped in Various Ways for 32 Years

Cropping	*Organic Matter Tons per Acre*	*Nitrogen Pounds per Acre*
Original crop land [41]	17.5	2,176
Continuous corn	6.4	840
Continuous oats	11.4	1,425
Continuous wheat	11.0	1,315
Corn, oats, wheat, clover, timothy	13.4	1,546
Corn, wheat, clover [42]	14.8	1,780

Note again that the land, although limed sufficiently to grow clover, was treated with neither farm manure nor commercial fertilizers. Hence the differences apparently are largely due to the crops grown and their sequence. Furthermore, it is safe to infer that if commercial fertilizers and

[40] Salter, R. M., R. D. Lewis, and J. A. Slipher, *Our Heritage—The Soil*, Extension Bul. 175, Ohio Agr. Exp. Sta., 1941, p. 9.

[41] At beginning of the experiment.

[42] Continued for 29 years instead of 32.

farm manure in normal amounts had been used the stabilization levels for the organic matter and nitrogen of the rotation plots would have been even closer to those of the land originally.

Economy in humus maintenance. Since the rate at which carbon is lost from the soil increases very rapidly as the organic content is raised, the maintenance of the humus at a high level is not only difficult but also expensive. (See Fig. 6:9.) It is, therefore, unwise to hold the organic matter above a level consistent with crop yields that pay best.[43] Just what

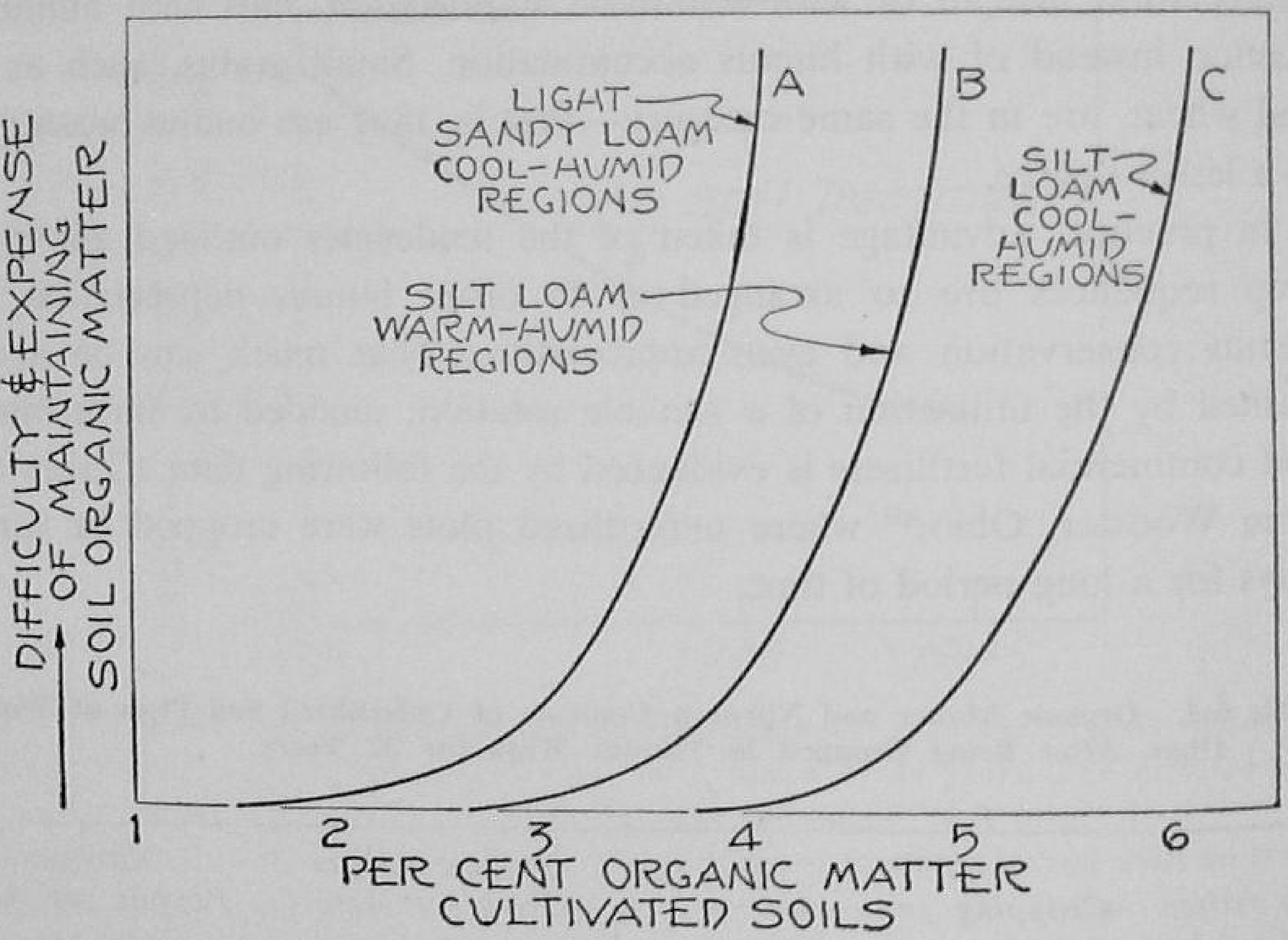

FIG. 6:9. *A generalized diagram showing how the difficulty and expense of maintaining the organic matter of cultivated soils increase as the support level is raised. While the curves are quite similar, their position in relation to the percentage of organic matter possible varies with* texture *(A vs C) and* climate *(B vs C). Other factors also are involved, especially the type of crop rotation employed.*

In practice the average amount of organic matter maintained in a cultivated soil should be held at the maximum level economically feasible.

this level should be will depend on climatic environments, soil conditions, and the particular crops grown and their sequence. Obviously, it should be higher in the chernozem region of North Dakota than in central Kansas where the temperature is higher or in northern Montana where the effective rainfall is lower. In any event, the soil organic matter, as well

[43] Russell, J. C., "Organic Matter Requirements of Soils under Various Climatic Conditions," *Jour. Amer. Soc. Agron.*, 19: 380–388, 1927.

as the nitrogen, should always be maintained at an economic maximum consistent with a suitable physical condition of the soil, satisfactory biochemical activity, an adequate availability of nutrients, and paying crop yields.

Good soil management, therefore, seeks to adjust the addition of organic residues, the physical and chemical conditions of the soil, the sequence of crops, and the losses through biological activity in such a way that paying crops may be harvested without reducing the humus supply of the soil below a definite level. Any system of agriculture that does not do this is improvident and unscientific.

CHAPTER 7

Forms of Soil Water, Their Movement, and Their Plant Relationships

A SOIL, in order to function as a medium for plant growth, must contain a certain amount of water. This moisture promotes the innumerable chemical, physical, and biological activities of the soil, acts as a solvent and carrier of nutrients, and in addition functions as a nutrient itself. The manner in which moisture is held in the soil and to what extent its translocations and amounts may be controlled must be reckoned with in any study of soil and plant relationships. As an introduction to these fundamental questions, let us consider first the nature of the pore spaces that make the presence of water in soils possible.

7:1. SIZE, SHAPE, AND ARRANGEMENT OF SOIL PORES

It is common observation that the profile of a normal mineral soil is made up of a series of horizons, each a porous mass of particles variable in size, shape, arrangement, and degree of compaction. Between these particles lies an intricate network of openings, just as heterogeneous as to size and shape as the solid fraction itself. Some of these pores, especially if the soil is sandy or well granulated, are likely to be large enough to facilitate a rapid downward movement of water by gravity. Others, in marked contrast, are so minute as to impede, if not entirely prevent, the liquid flow of water. Naturally, innumerable interstices of intermediate sizes occur, giving a continuous range from very large to very small.

The *macro* pores lie between the larger soil grains and granules and usually are connected by interstices and passages much smaller in diameter which are termed *micro* pores. The arrangement of the former is by no means regular although they often tend to occur in vertical strings. (See

Fig. 7:10.) And as might be expected, their outline and connections are tortuous beyond description. When large and continuous passages do occur, they usually are due to the vertical cracking of the soil during dry spells, to holes formed by earthworms and other soil fauna, and to channels developed by the decay of plant roots. The tendency of trees and such field crops as alfalfa and sweet clover to develop the latter type of fissure is well known.

Even the micro pores usually possess diameters that render them capable of some conduction of water. It must not be inferred, however, that the adjustment through them is necessarily rapid. Indeed, when they are very small or when plugged with colloidal matter, they may allow but a very sluggish movement, if any. Thus the flow of water from one large pore to another may be slow or rapid according to the nature of the connecting channels. Moreover, the size of the micro pores in an individual soil granule will determine in part the rate at which water may penetrate or be withdrawn from such an aggregate.

7:2. THE ADJUSTMENT OF WATER IN THE SOIL PORES

When water falls or is applied to the surface of a rather dry, well granulated field soil, it tends to move downward through the macro pores. As it enters, it replaces an equal volume of the soil air. The remaining gases, often large in volume, are entrapped in the smaller pores, especially those of the granules. Some, of course, is absorbed by the moisture. Thus some free air is insured in spite of the downward flood of water. At the same time moisture is being absorbed by the smaller pores and imbibed by the colloidal matter.

Downward movement. When enough water has entered the soil to satisfy the adsorptive capacity of the surface layer, the excess usually gradually sinks into the lower horizons. In the case of heavy and prolonged rains this drainage water penetrates farther and farther into the subsoil. Eventually it reaches a temporary or permanent water table or escapes into ditches or streams through natural or artificial channels. Even if the water-holding capacity of the furrow-slice is not satisfied, a slow downward adjustment will continue to take place through the smaller pores until equilibrium is more or less attained.

Capillary movement. In the meantime, if we are dealing with normal conditions, the evaporation of water probably has begun at the surface of the now moist soil. This loss promotes an upward film adjustment

called *capillarity*. This phenomenon is well exemplified by the upward movement of oil in a wick. Under the influence of this phenomenon water flows upward through the smaller soil pores. (See Fig. 7:6.) As a result, surface evaporation may be so markedly enhanced thereby as to seriously deplete the soil of water that might otherwise be used by plants.

This survey, brief as it is, suggests three things of great practical importance. Firstly, the soil has the capacity, not only of admitting water, but also of adsorbing and holding at least a part of it. Secondly, much of the water that finds its way into a soil later exhibits some type of movement, the nature depending on the conditions to which it is subjected. And thirdly, most of the water present in a soil sooner or later is lost as the natural cycle of events rolls around.

In short, water is an extremely variable and dynamic soil constituent. This implies energy exchange. In fact, energy exchanges are so obvious in every soil-moisture phenomenon that this approach to the subject will be adopted without further delay.

7:3. THE RETENTION OF WATER BY SOIL

When water is adsorbed by a soil, or by any other porous medium, energy as heat is liberated. This is easily demonstrated by moistening a dry soil under controlled conditions. Therefore, it is logical to suppose that, if the process is reversed and water is torn away, the removal will require a certain amount of work. This latter phenomenon will be used to introduce some of the simpler energy concepts relating to soil water.

Two forces account for the temporary fixation of water in soil. One is the attraction of the solid surfaces for water molecules (adhesion). This force is responsible for the adsorption of water (hydration) by silicate clays. These water molecules are held largely, but not entirely, by electrostatic forces operating in an electrical field that seems to exist on the external and internal surfaces of the soil colloidal particles. (See page 82.) Adhesion is operative only at the solid-liquid interface and hence the film of water established thereby even at its maximum, is very, very thin. (See Fig. 7:1.)

The adsorption described above is accompanied by a second and just as important a force—the attraction of water molecules for each other (cohesion). This force makes possible a marked thickening of

the films of water established by hydration until they attain macroscopic size.

Water held by these two forces, not only can keep the smaller capillary pores entirely full of water but also can maintain relatively thick films in the macropores. But as these latter films thicken they become progressively heavier until at least some of the water yields to gravity and moves downward through the large soil interstices. Such water obviously is very loosely held. (See Figs. 7:1 and 7:2.) Thus, when the soil is near saturation, it should be easy to remove a small increment of water, but as the moisture becomes less and less in a soil, the greater and greater will be the force necessary to tear away a unit amount.

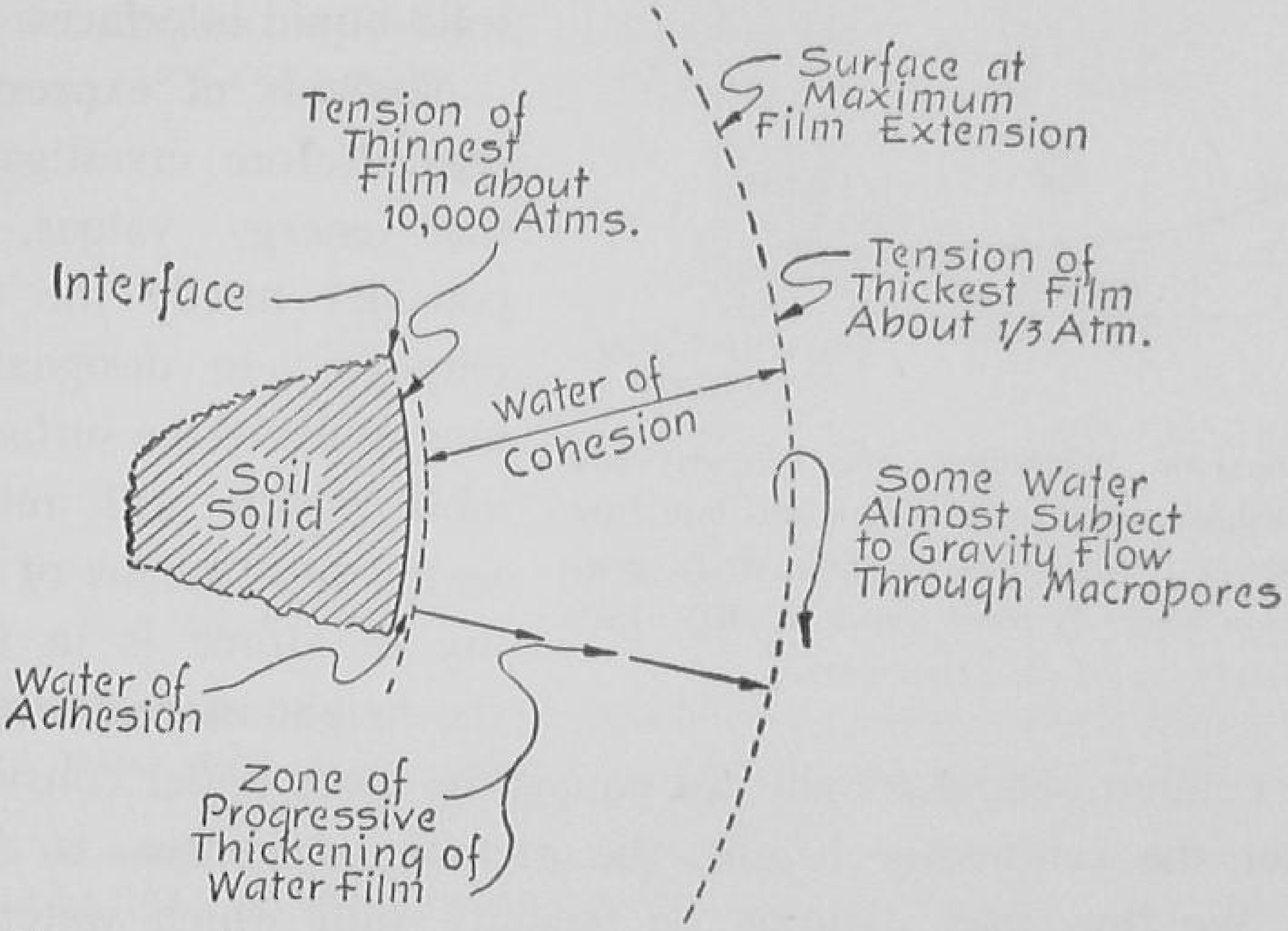

FIG. 7:1. *Diagrammatic representation of the progressive thickening of a water film in a macropore and the corresponding decline in the tension at which the surface molecules are held. While an increment of water can be extracted easily from the surface of a thick film, a similar removal from a thin film is much more difficult. Soil water is held in two ways*—adhesion *and* cohesion.

This dynamic concept is especially important for several reasons. It furnishes a thoroughly scientific basis for a classification of soil moisture. Also the movement of soil water can be expressed with greater precision, its availability to plants can be more accurately designated, and its practical control more satisfactorily explained.[1]

[1] For an over-all view of the various factors and correlations involved in the energy concept of soil water, see Kohnke, Helmut, "The Practical Use of the Energy Concept of Soil Moisture," *Proc. Soil Sci. Soc. Amer.*, 11: 64–66, 1946.

7:4. THE ENERGY CONCEPT OF MOISTURE RETENTION

Without going into details, it may be stated that it is quite possible by the use of certain methods to measure, under controlled conditions, the force necessary to remove successive increments of water from soil.[2] Thus, if we start with a soil saturated with water, the force required to remove each successive portion may be measured. (See Fig. 7:2.) This gives an evaluation in energy units for practically all of the moisture of any particular soil, including even that adsorbed with such tremendous rigidity at the solid-liquid interfaces.

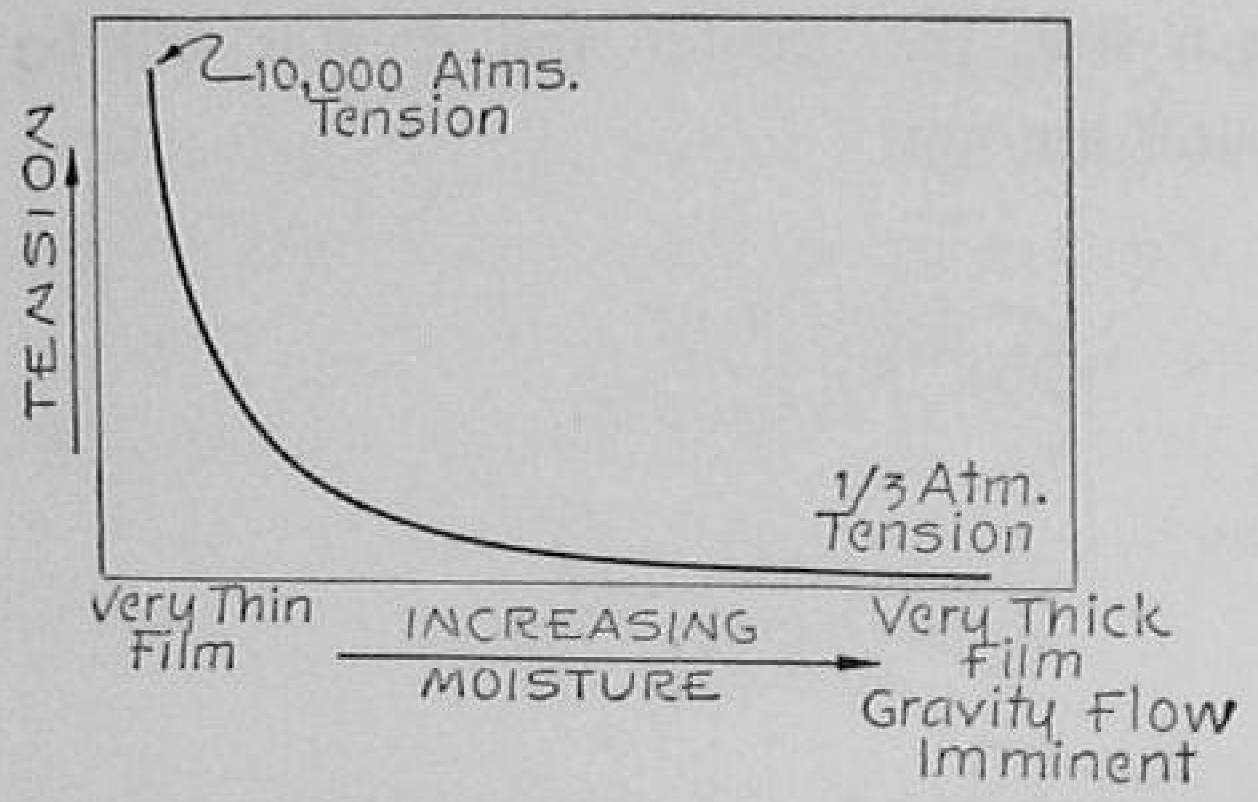

FIG. 7:2. *Diagram showing the logarithmic change in tension at the surface of a soil moisture film as the latter is thickened or thinned. In general the tension range is from about 10,000 atms. to approximately ⅓ of an atmosphere.*

Methods of expressing energy. Before investigating actual energy values, let us consider briefly the methods employed in designating the magnitude of the surface forces with which soil retains its water. One means of expressing the force is in terms of the height in centimeters of a unit water column, whose weight just equals the force under consideration. The greater the centimeter height, the greater, of course, is the force measured. We thus may express the tenacity with which water is held by soils in centimeters or we may convert such readings into other forms. In any case, the method of expressing the negative tension of moisture films should be as simple as possible.

Perhaps a more generally accepted method is that of *atmospheres*—the standard atmosphere, that is the average air pressure at sea level, being 14.7 pounds per square inch. The negative pressure exerted by a column of water 10 centimeters high under standard conditions is about 1/100 of an atmosphere; that by a column 100 centimeters high, 1/10 of an atmosphere; that by a 1000 centimeter column of water, approximately 1 atmosphere of tension and so on. The table which appears below[3] presents further

[2] For further information, consult Baver, L. D., *Soil Physics,* John Wiley and Sons, Inc., New York, 1948, pp. 210–212 and Richards, L. A., "Methods of Measuring Soil Moisture Tensions," *Soil Sci.,* 68: 95–112, 1949.

conversions. Study the table very carefully, as it will be necessary to consult it frequently.

Energy-moisture content correlations. By the determination of tension values at various moisture contents for particular soils, graphs may be constructed indicative of their moisture-energy relationships. In order to point out the significance of such curves, generalized drawings are presented representative of three texturally different soils—a sand, a sandy loam, and a silt loam. (See Fig. 7:3.) It is to be noted that atmospheres of tension are plotted against percentages of moisture based on dry soil.[4]

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3 *A Table of Pressure Equivalents*

Height of a Unit Column of Water in Centimeters	*Approximate Atmospheres of Pressure*	*Equivalent pF Values*
1	1/1000	0
10	1/100	1
100	1/10	2
346	1/3	2.54
1,000	1	3
10,000	10	4
15,849	15	4.2
31,623	31	4.5
100,000	100	5
1,000,000	1,000	6
10,000,000	10,000	7

The transfer from centimeters of pressure to atmospheres is simple. Assume a column of water with a base one inch square and 1000 centimeters high. Since 1000 cm. = 393.7 inches, the column would contain 393.7 cubic inches of water. A cubic inch of water weighs .03612 pounds. Hence the pressure in pounds per square inch would be 393.7 × .03612 or 14.22. This is approximately 1 atmosphere (.9674).

Another method of evaluating soil water tensions has been used rather extensively. In this method energy values are expressed as the logarithm of the centimeter height of the water column in any given case. This value is called for convenience pF. Thus the force equivalent to the weight of 100 centimeters of water corresponds to a pF of 2; that of 1000 centimeters to a pF of 3; and so on until the extreme force with which water is held by soils is reached. This is approximately 10,000,000 centimeters, or a pF of 7. Since this method of expression is used in the earlier literature dealing with soil moisture tensions, pF values corresponding to atmospheres of pressure are included in the table above.

4 The usual method of expressing the amount of water present in a soil is in terms of percentage based on dry soil. Thus, if 100 gms. of moist soil (soil + water) when dried lose 20 gms. of water, the 80 gms. of dry matter are used as a basis for the percentage calculation. Therefore, (20 ÷ 80) × 100 = 25 per cent. The weight of the wet soil is undesirable as a basis for calculation since it changes with every moisture fluctuation.

A moisture determination on a sample of soil is generally carried out as follows: 100 gms. of the sample, after thorough mixing, is weighed into a suitable dish and air-dried. The sample is then placed in an oven and heated at 100° or 110° C. for seven or eight hours. It is then cooled in a desiccator and weighed. The loss in weight

It is clearly apparent from the graphs that some of the water present in soils is held under tremendous negative pressures, approaching 10,000 atmospheres. This has already been suggested. On the other hand, when a soil is well supplied with water, a very slight suction is sufficient to withdraw a minute amount. Moreover, the tension curves show all gradations between these extremes thus indicating a gradual change in energy of retention. Unless zones of demarcation are arbitrarily established, it will be difficult to develop a clear cut classification of soil water on the basis of energy units.

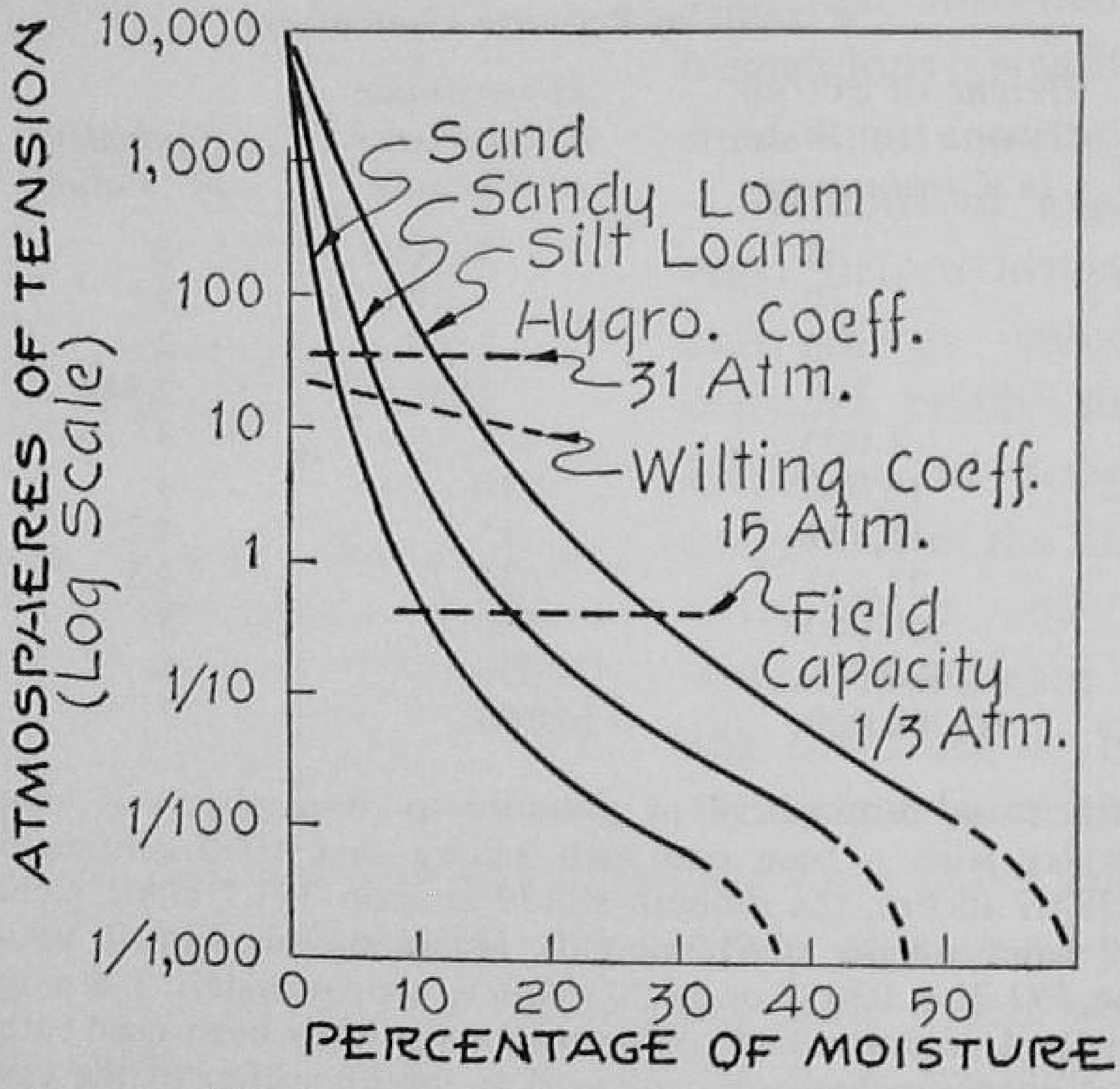

FIG. 7:3. *Tension curves for three representative mineral soils. The atmospheres of negative pressure are plotted against percentage of soil moisture present. Note the rapid drop in tension as the amounts of soil moisture increase and the films thicken. The silt-loam has, of course, the greatest water capacity.*

It must always be borne in mind that pressure values express only the tension of water at the liquid-air interfaces—that is, moisture at the surface of the film. Thus a thin film might be subject to a negative pressure of 100 atmospheres but, if thickened by additions, the water occupying the position of the original film will be subject to considerably less tension and will move much more freely than before. This must not be forgotten

is water. The moisture is then calculated as a percentage based on the dry matter of the soil.

in the use of tension values, otherwise a serious misconception is entertained.

Further examination of the illustrative curves (Fig. 7:3) will show that they vary characteristically with soil texture. Not only do the heavier soils retain a greater percentage of moisture in total but the ascendancy is also evident through the entire energy range. This is to be expected as the heavier soils, because of their greater percentage of total colloidal matter, usually present a greater total pore space as well as a much greater adsorptive surface.

7:5. THE HYGROSCOPIC COEFFICIENT, FIELD CAPACITY, AND MAXIMUM RETENTIVE CAPACITY

Certain important and more or less critical points may be established with considerable accuracy on the negative tension curve of any soil. At the moment, three are of especial interest and significance—the *hygroscopic coefficient, field capacity,* and *maximum retentive capacity.* (See Fig. 7:3.) They will be considered in order.

Hygroscopic coefficient. When a dry sample of soil is exposed to water vapor, it will take up moisture. And the amount adsorbed will depend on the nature and magnitude of the surface presented, the temperature, and the degree of humidity. The moisture thus adsorbed is designated as water of hydration, water of adhesion or commonly *hygroscopic* water. Naturally when the air saturation is at or near 100 per cent, the maximum amount of such moisture will be acquired. As determined,[5] the hygroscopic coefficient usually approaches this amount and is conveniently expressed in *percentage* based on dry soil.

It will be noted by reference to the tension curves (Fig. 7:3) that the hygroscopic coefficient for mineral soils falls at or near a pressure of about 31 atmospheres. Hence, it may be used as a measure of the soil water that is held at very high tensions, so high, in fact, as to render most of it almost wholly inactive biologically. The forces effective at the hygroscopic coefficient are due mostly to the attraction of the soil colloids

[5] The method of determining the hygroscopicity of a soil at any given vapor pressure is simple in outline. Air-dry soil in thin layer is exposed to an atmosphere of definite humidity under conditions of constant temperature. When equilibrium is reached, the moisture content of the sample is determined.

Many investigators favor the use of a 3.3 per cent solution of sulfuric acid which gives a relative humidity at laboratory temperature of 98.2 per cent and a tension of about 31 atmospheres. See Baver, L. D., *Soil Physics,* John Wiley and Sons, Inc., New York, 1948, pp. 70–79 and 251.

for water molecules. Consequently, this value may be used comparatively and even analytically [6] as a measure of the proportion of the soil solids in the colloidal state. These considerations justify the determination of such a factor, arbitrary though it may be.

Field capacity. When a well granulated soil is fully saturated with water and adequate opportunity for drainage is provided, some of the water will respond to gravity and move downward. Practically all of the water held at a tension of about one-third of an atmosphere or less ultimately is subject to such movement. (See Fig. 7:1.) This means that much of the water is soon cleared from the macropores and even some of that in the larger capillaries may be appreciably affected. This downward movement is spoken of as *percolation* or more commonly as *drainage.* When this excess or superfluous water has been fully pulled out of any horizon, the soil therein is said to be at *field capacity* or *maximum capillary capacity.*

Analytically the field capacity of any soil layer is the percentage of water (based on dry matter) that it can retain against gravity when adequate drainage is afforded. At this time the force necessary to remove an increment of water from the film surface will be about one-third of an atmosphere. Thus, a second important point can be located on the negative tension curve of any soil. (See Figs. 7:3 and 7:4.)

Soils of heavy texture and high colloidicity usually exhibit high field capacities. Organic matter exerts a similar influence. Compaction and granulation are also important factors. The compaction of a sandy soil will often increase its water-holding powers, while the effect is likely to be just the opposite with a soil of a heavy nature. Granulation in most cases, especially with the finer textured soils, tends to enhance the amount of moisture retained against gravity.[7]

[6] For a brief outline of this method see bottom of page 109.

[7] A laboratory method often is used to obtain an arbitrary moisture figure, called the *moisture equivalent,* which closely approximates, especially with fine textured soils, the field capacity. The moisture equivalent is obtained by subjecting a sample of wet soil, held in a vessel of specified dimensions, to a centrifugal force of 1,000 times gravity.

Due to the conditions to which the short column of soil is subject as the pressure is applied, the average tension is equivalent to a pull on a free column of only 500 times the force of gravity. Hence the moisture equivalent corresponds to about one-half atmosphere of tension.

Briggs, L. T., and J. W. McLane, *The Moisture Equivalent of Soils,* Bulletin 45, Bureau of Soils, U. S. Dept. of Agriculture, 1907.

See also Browning, G. M., "Relation of Field Capacity to Moisture Equivalent in

Maximum retentive capacity. Before considering the classification of soil water one more moisture value should be mentioned—the *maximum retentive capacity*. This may be defined as the moisture percentage in a soil when its total pore space is completely filled with water. An approximation of such conditions may be obtained if a very thin layer of soil (5–10 millimeters deep) is allowed to absorb water from a free water table.[8] This minimizes the influence of gravity, and results in a tension of no more than perhaps .01 or even .001 of an atmosphere.

The maximum retentive capacity of a given soil is determined, of course, by the amount of total pore space available. Practically speaking, it is very unwise to allow a crop soil to remain at this level for very long periods of time. Such a saturated condition allows practically no aeration and is consequently harmful to most crop plants.

7:6. THE PHYSICAL CLASSIFICATION OF SOIL MOISTURE

On the basis of the three coefficients considered in the previous section, it is possible to classify soil water very simply under three heads—*hygroscopic, capillary,* and *gravitational.* (See Fig. 7:4.) Two other forms, both already mentioned—*water of crystallization* held by soil minerals, especially the silicate clays (page 82), and the *water vapor* of the soil air—need not be considered here.

The first form of soil water mentioned above, the *hygroscopic*, includes all the moisture present at the hygroscopic coefficient and is held with a tension of 31 atmospheres and greater. The second type is the moisture of the soil that exhibits the fluid adjustment commonly spoken of as capillarity.[9] This so-called *capillary* water is extremely variable in amounts. When at a minimum its tension is approximately 31 atmospheres. When at maximum, that is at field capacity, its negative pressure is only about ⅓ of an atmosphere. (See Fig. 7:4.) The water at tensions less than ⅓ of an atmosphere, and that tends to move out of the soil due to the pull of gravity, is distinguished by the term *gravitational*. In well-drained soils it soon ceases to be an important factor.

Soils of West Virginia," *Soil Sci.*, 52: 445–450, 1941 and Smith, R. M., and D. R. Browning, "Soil Moisture Tension and Pore Space Relations for Several Soils in the Range of the Field Capacity," *Proc. Soil Sci. Soc. Amer.*, 12: 17–21, 1947.

[8] See Hilgard, E. W., *Soils*, The Macmillan Company, New York, 1911, p. 209.

[9] If the reader does not clearly understand the mechanics of this type of water adjustment, consult section 7:11 on page 197.

It must always be remembered, however, that such a classification implies no lines of demarcation or clear-cut distinctions; in fact, considerable overlapping occurs. The terms are merely used as a convenient way of referring to soil water within certain energy ranges and possessing in general certain types of movement. And the differences, so often considered as definitely characteristic, vary gradually and progressively.

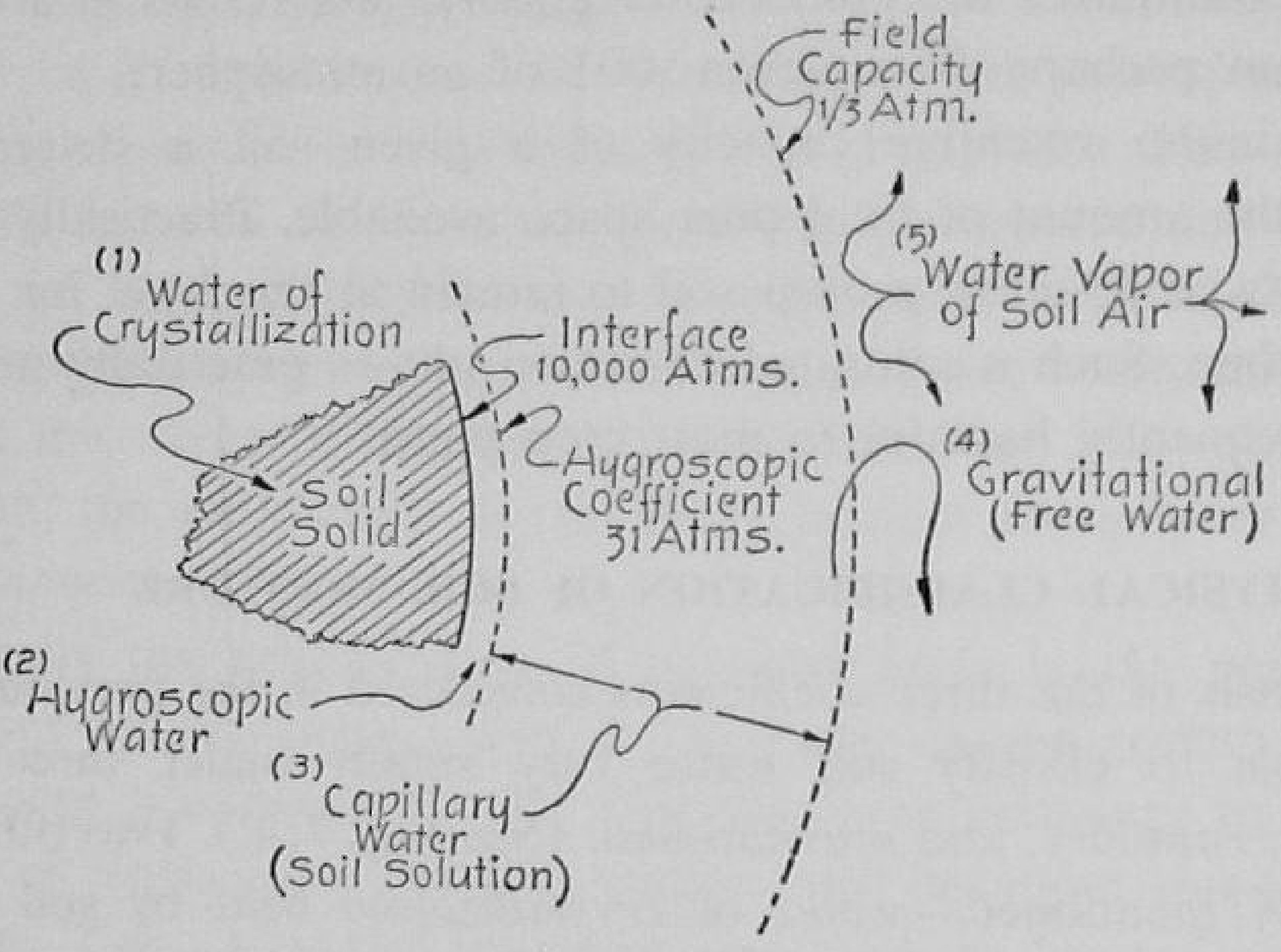

FIG. 7:4. *Diagram showing the five types of soil water that may be present in soils—(1)* water of crystallization, *(2)* hygroscopic, *(3)* capillary, *(4)* gravitational, *and (5)* water vapor. *Of these the capillary and gravitational water receive the most attention in practice. Note that the soil solution is practically coincident with the capillary moisture.*

7:7. HYGROSCOPIC WATER

The hygroscopic water which is held so tenaciously by the soil exists as a very thin film at the solid-liquid interfaces that are exposed both externally and internally by the soil particles and granules. This film, thought to be made up of not over fifteen or twenty layers of water molecules, has a maximum thickness that probably does not exceed 4 or 5 millimicrons. Because of the tremendous pressures exerted upon them, approaching 10,000 atmospheres at the solid-liquid interface, the molecules are closely packed and most of the layer is nonliquid. It must be remembered, however, that in the neighborhood of the hygroscopic coefficient the tension at the outer film surface is much less, approximately 31 atmospheres. Thus, a transition to the liquid state gradually takes place as the film continues to thicken.

Since much of the hygroscopic water is in a nonliquid state and as such is immobile, it probably participates but to a slight degree in the biological activities of soil. However, when a hygroscopically saturated soil is exposed to a partially saturated air, hygroscopic water will be lost due to vapor-pressure adjustments. The drier the air, the lower will this form of water tend to become. For convenience of determination, it is generally assumed that all but a small portion of the hygroscopic water that happens to be present will be driven from a soil by heating for eight or ten hours at a temperature of 100° to 110° C.

As already intimated, the hygroscopic coefficient, as commonly defined (page 189), varies considerably from soil to soil. For a sandy loam, containing little organic matter, the hygroscopic coefficient may be as low as 1 or 2 per cent by weight. In a heavy clay, with 4 or 5 per cent of organic matter, it may rise as high as 15 or even 20 per cent. This is because of the tremendous interface presented by the soil solids. With peat soils the quantity is still greater, in some cases reaching 60 or 70 per cent. This relatively inactive water thus is surprisingly large in some soils.

7:8. CAPILLARY WATER

Capillary water is that held between the field capacity and hygroscopic coefficient. (See Fig. 7:4.) The water in the so-called capillary zone thus shows a considerable range in energy values. These different energy levels are reflected in movement differences in spite of the fact that all of the capillary water is considered to be in a fluid state. At the higher tensions, say between 15 and 31 atmospheres, capillary adjustment is very sluggish indeed. Comparatively ready movement does not occur until the water film thickens and pressures in the neighborhood of the maximum field capacity (.33 of an atmosphere) are reached. The mechanics of this capillary adjustment are simply explained on page 197 and ff.

An idea of supreme importance should not be lost sight of. As a result of its energy relations, the capillary water is the only fluid water bearing solutes that remains in the soil for any length of time if drainage is satisfactory. Consequently, it functions, chemically and physically, in such ways as to justify the designation of *soil solution*. The hygroscopic water is largely nonliquid, while the gravitational water usually is too transient to be considered as an integral part of the soil. The soil solution is coincident, therefore, with that part of the liquid water that remains in the soil after free drainage has taken place. (See Fig. 7:4.)

The conditions that influence the maximum amount of capillary water that soils will hold are numerous and variable. Three of the most important in a practical way will be briefly considered—(1) texture, (2) structure, and (3) organic matter.

Influence of texture, structure, and humus. The finer the texture of a mineral soil, the greater is likely to be its capillary capacity. The validity of this statement is clearly substantiated by the tension curves of Fig. 7:3. This is due to the porosity of the colloidal materials and to the great number of minute interstices that carry water films.

As soils become more granular, especially if organic matter is one of the granulating agents, the spaces of microscopic size are likely to be enlarged and their water capacity greatly increased. And since much of the capillary water is lodged in such pores, an increase in capillary retention tends to occur. The compaction of heavy soils by reducing their porosity is also sure to reduce their capacity to hold capillary water, but with sands or sandy loams the opposite effect is likely to result. This is because the compaction, while reducing the total pore space, may increase the number of pores of capillary size.

Humus is regarded as having a very high capillary capacity, far exceeding the mineral portion of soil in this respect. Not only is the porosity of such material very high but interstices of microscopic size make up a large proportion of the total pore space. It is no wonder that the soil specialist is insistent upon a granulation that is encouraged by the maintenance of an adequate supply of organic matter. He realizes the biological importance of the soil water held at the lower tensions and that one of the problems of water control is to maintain or even enlarge such soil capacity.

Data reported in Table 7:1 illustrate the variations in the amounts of hygroscopic and capillary water that soils may retain and the influence of texture and organic matter thereon. Moisture equivalent figures (see note, page 190) are considered as approximating field capacities. While the data are expressed as percentages based on dry matter, their energy significance should not be overlooked. The negative tensions increase as the moisture percentages go down.

Several relationships are clearly evident even from a casual examination of the data. The amounts of hygroscopic and capillary water, as well as the maximum retentive capacity, are correlated definitely with both the texture and the organic matter contents of these soils. From what we

know about colloidal characteristics this is no surprise but it is to be noted that the relationships are by no means uniform.

Table 7:1. Hygroscopic and Capillary Water Capacities of Various Soils

Soils	1 *Organic Matter*	2 *Hygroscopic Coeff.*	3 *Field Capacity (Moisture Equiv.)*	4 *Capillary Water (Column 3–2)*	5 *Maximum Retentive Capacity (Tension near 0)*
	Per Cent[10]	*Per Cent*	*Per Cent*	*Per Cent*	*Per Cent*
Western Soils[11]					
Sandy soil (Nebr.)	1.22	3.3	7.9	4.6	34.2
Red loam (N. Mex.)	1.07	10.0	19.2	9.2	49.0
Silt loam (Nebr.)	4.93	10.2	27.8	17.8	60.9
Black adobe (Ariz.)	2.22	12.9	25.8	12.9	60.3
Iowa Soils[12]					
Dickinson fine sand	2.13	3.4	7.6	4.2	44.5
Clarion sandy loam	3.01	6.9	15.5	8.6	58.0
Marshall silt loam	3.58	10.4	24.0	13.6	76.5
Wabash silty clay	5.91	16.1	30.4	14.3	87.0

Moreover, there seems to be no dependable ratio between the amounts of hygroscopic water and capillary water that soils can retain. The capillary moisture, while usually greater than the hygroscopic, in some soils is less. Differences in the nature of the clay and organic matter present in the various soils as well as structural variations may account for the lack of correlation observed. Thus, there seems to be no way of accurately calculating the values under consideration. Direct determinations must be made.

7:9. GRAVITATIONAL WATER

Experimental evidence indicates that water held in the soil at tensions of ⅓ of an atmosphere or less will, under suitable conditions, respond to gravity pull and move downward. The water thus affected usually is that present in the macro pores. (See Fig. 7:10.) It is through these channels and their connecting interstices that the removal is effected. The energy relations of this so-called free water can be clearly defined. Consequently,

[10] All percentages are based on dry weights.

[11] Alway, F. J., and G. R. McDole, "The Relation of Movement of Water in a Soil to Its Hygroscopicity and Initial Moisture," *Jour. Agr. Res.*, 10: 391–428, 1917.

[12] Russell, M. B., "Soil Moisture Sorption Curves for Four Iowa Soils," *Proc. Soil Sci. Soc. Amer.*, 4: 51–54, 1939.

it is necessary only to briefly emphasize why gravitational water, even though it is superfluous or excess in nature, receives so much attention. Two outstanding reasons are evident—(1) the necessity of adequate drainage, and (2) the loss of plant nutrients that its removal entails.

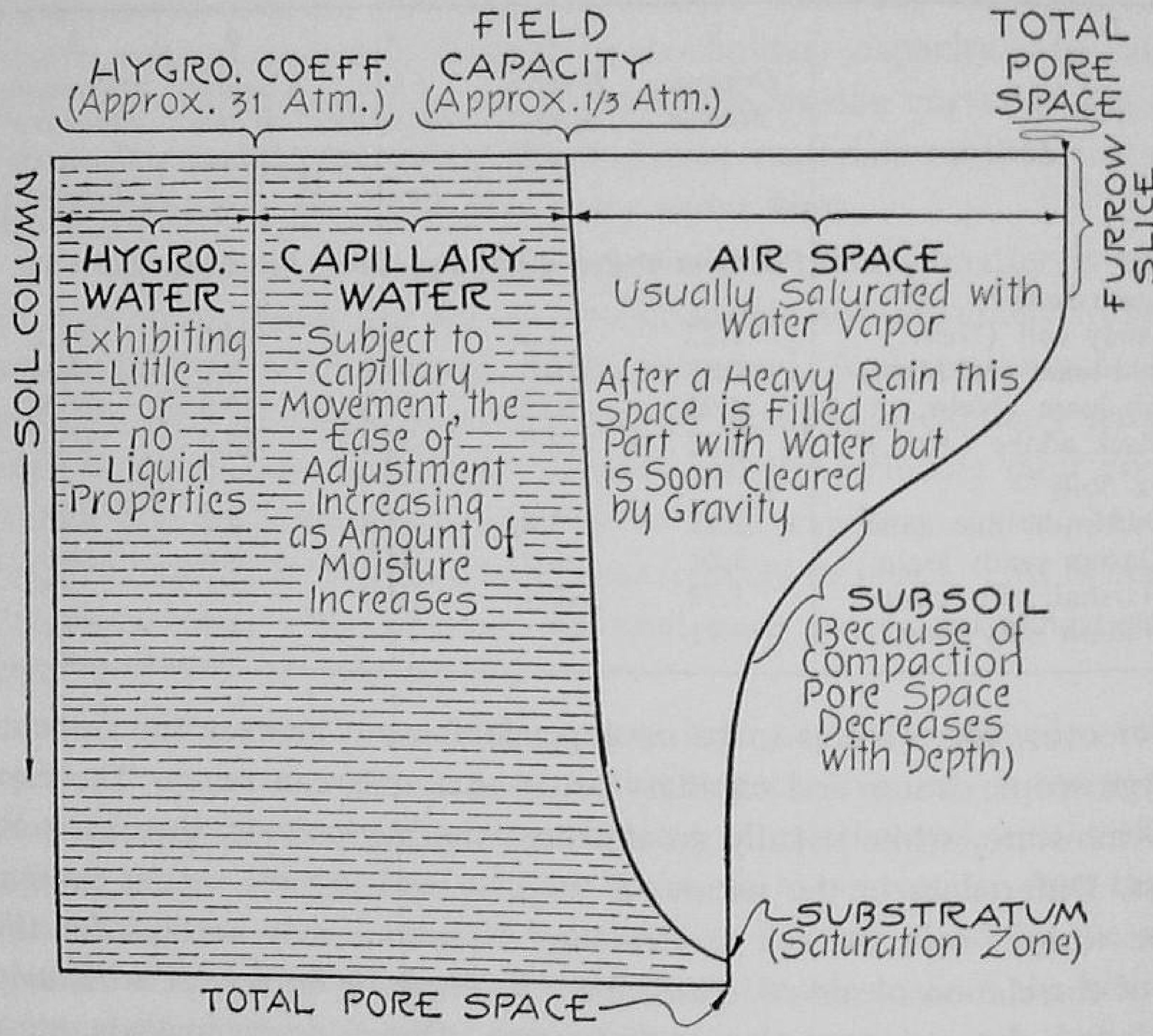

FIG. 7:5. *Diagrammatic representation of the moisture distribution in a soil column of uniform texture saturated at the bottom but well drained at the surface. Three forms of soil water are shown*—hygroscopic, capillary, *and* drainage *or* free. *The latter when present occupies the volume designated in the diagram as airspace. The tension ranges are shown in atmospheres of pressure. The exact quantity of moisture present at any particular tension will, of course, vary with the soil under consideration and it's physical condition.*

Since the gravitational water occupies the large porte spaces of the soil, it excludes air and interferes with oxidation. (See Figs. 7:5 and 7:13.) A poorly drained soil is soon unsatisfactory for the production of most crops. The normal soil processes, both chemical and biological, are slowed down and favorable physical relations are weakened. In fact, the whole cycle of events on which most higher plants depend is thrown out of adjustment by excess water.

Most persons know that the removal of the gravitational water entails the loss of considerable amounts of nutrient materials, and that this greatly augments the difficulty of maintaining the fertility of soils. The magnitude of this loss is, however, seldom realized nor its seriousness fully appreciated. A full discussion of this phase will be found in section 9:3 on page 246.

The reader who may wish to consider the plant relationships of soil moisture without further delay, or additional technical preparation, should turn directly to section 7:18, page 210, and from there complete the chapter. Although the omitted sections will greatly strengthen the technical concept of the reader, they are not absolutely essential from the practical standpoint. They are, nevertheless, very interesting.

7:10. THE MOVEMENT OF SOIL WATER—TYPES OF

In discussing the characteristics of the different forms of moisture commonly recognized in soils, adjustment and movement have been stressed again and again. And rightly so, as water is a notably dynamic soil constituent. Three types of movement within the soil are recognized—*capillary adjustment, percolation,* and *vapor equalizations.* So important, both theoretically and practically, are these three changes in position that they merit individually more than passing references. Their examination in the following sections will be climaxed by a consideration of their plant relations, a particularly significant phase.

Before an explanation of the first type of water movement—capillary adjustment—can adequately be made, certain fundamentals should be clearly in mind. They will be briefly reviewed herewith.

7:11. CAPILLARY FUNDAMENTALS AS THEY RELATE TO SOIL WATER

First consider an ideal case of capillarity. If the lower end of a clean glass tube of capillary dimensions is placed vertically in water, the liquid will rise in the tube above the level of the water surface outside. (See Fig. 7:6.) The phenomenon, called *capillarity,* is initiated by the attraction of the glass for the water (adhesion) which causes the liquid to rise around the sides of the tube. At the same time, because of the attraction of the molecules of water for each other (cohesion), that portion of the liquid unaffected directly by adhesion is progressively pulled upward, as adhesive forces operate, thus keeping the column intact.

In other words, tensile forces at the liquid-air interface are powerful enough to support that portion of the column not directly attracted by the walls of the tube. Hence, a continuous column of water rises until its weight just equals the adhesive attraction pulling the liquid upward. Thus, the mechanics of

capillary adjustment as it operates in this particular case can be very simply stated.

Three additional ideas are pertinent. Firstly, "the surface of the elevated water column will be concave," that is, it will sag in the center. This is because of the weight of the water column which is being supported by its surface film. And, naturally, the longer the column the greater will be the weight per unit of supporting surface at the top of the column and the more pronounced will be the concavity or sag.

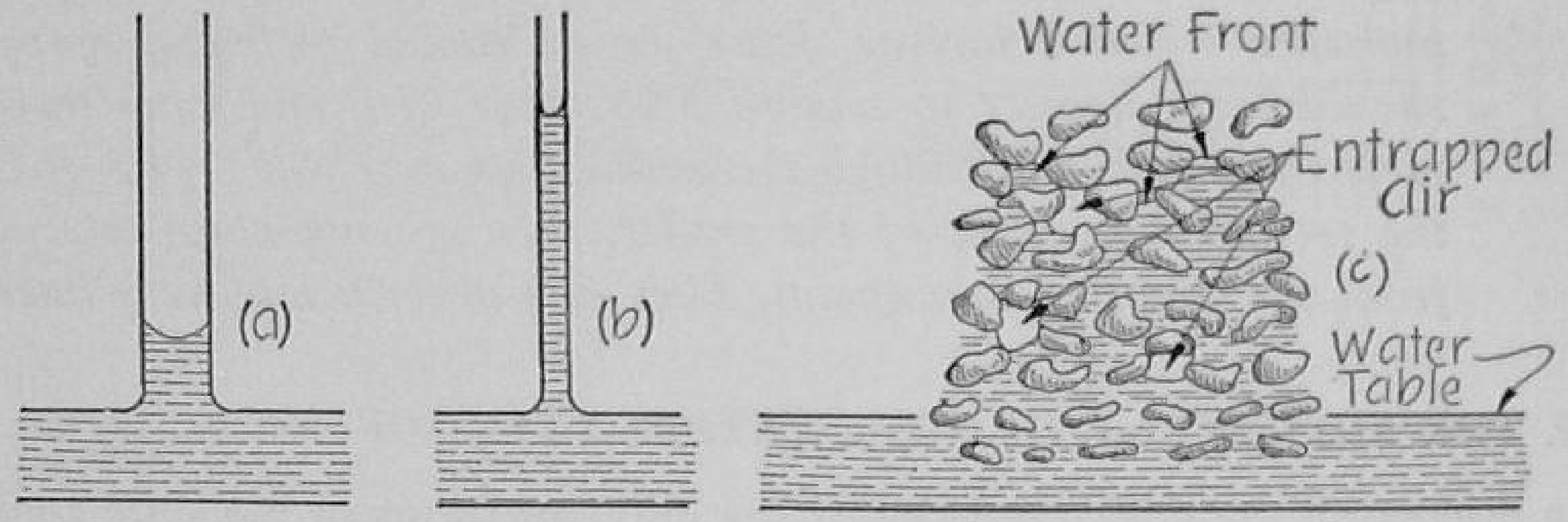

FIG. 7:6. *The upward capillary movement from a water table, (a) in a large glass capillary tube, (b) in a small capillary tube, and (c) in a soil column. Note the higher rise in the small capillary tube and the greater curvature of film. While the mechanism is the same in both the tubes and in the soil, the adjustment is extremely irregular in the latter due to the tortuous nature of the channels, their variability in size, and the presence of entrapped air.*

Secondly, "the smaller the capillary channel, the higher will be the rise of the water column." This is because for a unit section of the capillary tube, the amount of adhesive surface per unit weight of water is greater in a small tube than in a larger one.[13] Thus, a longer column of water can be supported by the adhesive attraction exerted by the walls of the smaller tube when equilibrium is attained,[14] that is, when the capillary column is at a maximum height. And because of the greater length attained by the column in the smaller tube, a

[13] The wet perimeter of a cylinder varies directly with its diameter (πd) but the volume of the cylinder varies with the square of its diameter ($\frac{1}{4}\pi d^2 h$). Therefore, as the diameter of a unit cylinder is reduced, its wet perimeter decreases relatively less rapidly than does its volume. Hence, the ratio of the adhesive surface of a unit section of a cylinder to the volume of water held up by it will increase as the cylinder becomes smaller.

[14] This truism can be established mathematically as follows: The height (h) to which water rises in a capillary tube is expressed by the formula:

$$h = \frac{2T}{rdg}$$

where T is surface tension in dynes per centimeter, r, the radius of the tube in centimeters, d, the density of the liquid, and g, gravity in dynes per centimeter. It is obvious from the formula that the smaller the radius of the tube, the higher will be the rise of the liquid in it.

greater concavity, as already suggested, will be exhibited by its surface film. The truisms of this paragraph are graphically shown in Fig. 7:6.

Thirdly, the attractive force of the water molecules for each other is manifest at all liquid-air interfaces by a phenomenon called *surface tension.*[15] This stress, which is evidenced by the tendency of the film to contract, reduces the water-air interface in any particular case to the least possible area. In other words, surface tensions operating at the top of a capillary column of water will tend to develop a plane surface. This tendency to reduce the curvature of the concave film creates an upward pull on the water mass below. Moreover, it is quite obvious that the greater the curvature of the film, that is, the greater the departure from a plane surface, the more marked will be the resistence to further extension and the greater will be the pull exerted by the film in its attempt to restore its surface to a minimum. This can be easily proven mathematically.[16]

The principle cited above—"the greater the concave curvature of a water film the greater will be the pull developed by surface tension"—is very important in a capillary complex such as that existing in soils where many concave films of different degrees of curvature exists. Obviously there will be a tendency for the water to move towards the points in the system where the greatest concavity of film exists, for here will occur the greatest pull due to the influence of surface tension. This simple concept will be applied later in explaining the capillary adjustments of the film water of field soils. (See Figs. 7:6 and 7:8.)

[15] Surface tension may be precisely defined as that property, existing in the surface films of all liquids, which tends to reduce the contained volume to the form exposing the least amount of superficial area. Naturally this surface film is very thin since it represents the greatest distance through which two particles will exert mutual cohesion. Particles lying in the liquid but below this film are equally attracted on all sides and are, therefore, in equilibrium. But those within the film itself are attracted inward to a greater degree than outward and a surface stress or tension results.

Since this film is under stress, it tends to contract and in the case of a concave film an outward pull will be exerted. With a convex film, such as exists around a globule of water, the pressure will be inward.

[16] The proof is usually made on the basis of a globule of liquid where the film is convex.

The pressure (P) developed by surface tension in dynes per centimeter (T) is commonly expressed by the following formula in which r is the radius in centimeters of the drop of liquid under study:

$$P = \frac{2T}{r}$$

As the drop becomes smaller, its radius (r) diminishes and the pressure (P) developed by surface tension becomes greater. Since the curvature of the film increases as the drop becomes smaller, it is obvious that "the greater the curvature of the film, other conditions remaining constant, the greater will be the pressure developed by surface tension."

In the case of a concave film such as is present in a glass capillary, the formula is the same except that the values of P and r are negative.

7:12. UPWARD CAPILLARY MOVEMENT FROM A SOIL WATER TABLE

When water moves upward from a water table through the capillary interstices of a soil, the phenomenon is identical in principle to the rise already described for a glass tube. Adhesion and cohesion are active in exactly the same way. The water columns as they elongate are subject to the same mechanisms and concave films are established at their summits. The curvatures of these films will depend upon the sizes of the interstices at these points and upon the lengths of the individual columns.

In contrast with the adjustment in a glass tube, the capillary movement in soils ordinarily proceeds very irregularly and spasmodically. Also, the rising front of water is greatly distorted and deformed. The swelling of the soil colloids and the presence of entrapped air impede the rate of movement while many of the large interstices cannot be bridged at all. As a result, the adjustment becomes slower and slower until the water front halts at a comparatively short distance above the water table. At the capillary front the pores are almost completely filled but the soil layers above are still at or near their original moisture content. The line of demarcation between the two layers is surprisingly sharp and the tension at the water front is probably in the neighborhood of ⅓ of an atmosphere. (See Fig. 7:6.)

Were the conducting capillaries continuous, uniform in size, and unobstructed by entrapped air and viscous colloids, capillary movement upward from a water table would be quite effective. And it would be possible to calculate the probable height of rise and its rate.[17] But soils in nature present a complicated labyrinth of pores, tortuous and variable in size and shape. Moreover, they are clogged with colloidal matter of various kinds and partially filled with air, some of which is very difficult to dislodge. And more than this, many of the interstices are so large as to be capillarily noneffective. (See Fig. 7:6.) Consequently, breaks in the water column are almost sure to occur. This alone presents a most serious obstruction as no upward capillary movement occurs unless the interstitial cross section is held full of water. As a result, the adjustments in any particular soil under field conditions are likely to be rather uncertain both as to height and rate of rise.

Height of capillary rise. Usually the height of capillary rise is greater with the heavier soils, if sufficient time is allowed and the interstices are not too small. This is readily explained on the basis of the small size and the continuity of the capillaries. Moreover, the proportion of the pore space made up of very large interstices is comparatively low. With sandy soils the adjustment is rapid but so many of the pores are either noncapillary or only weakly exhibit this capacity, that the height of rise cannot be great.

[17] Puri maintains, however, that the laws of surface tension and capillarity can be applied with some precision if the pores are kept full of water and no obstructions occur. Puri, A. N., "Physical Characteristics of Soils, V. The Capillary Tube Hypothesis of Soil Moisture," *Soil Sci.*, 48: 505–520, 1939.

The situation in any particular case is sure to be greatly modified by the particular structural condition involved. Compacting a sandy soil and thereby reducing the size of the capillaries and increasing their number may increase the height of water rise. But with a heavy soil compaction as well as the infiltrated clay are likely to impede capillarity greatly. Hence, granulation, especially with a soil of fine texture usually tends to enhance the rate of adjustment if not the height of rise.

In all cases the original moisture content of the soil is extremely important, since a fairly dry soil resists wetting, sometimes to a marked degree. Consequently, a moist soil encourages not only a higher but also a faster rise. More tangible ideas as to the influence of texture on the height and rate of water rise through soil from a water table may be obtained by consulting Fig. 7:7 drawn from data presented by Loughridge of California.[18]

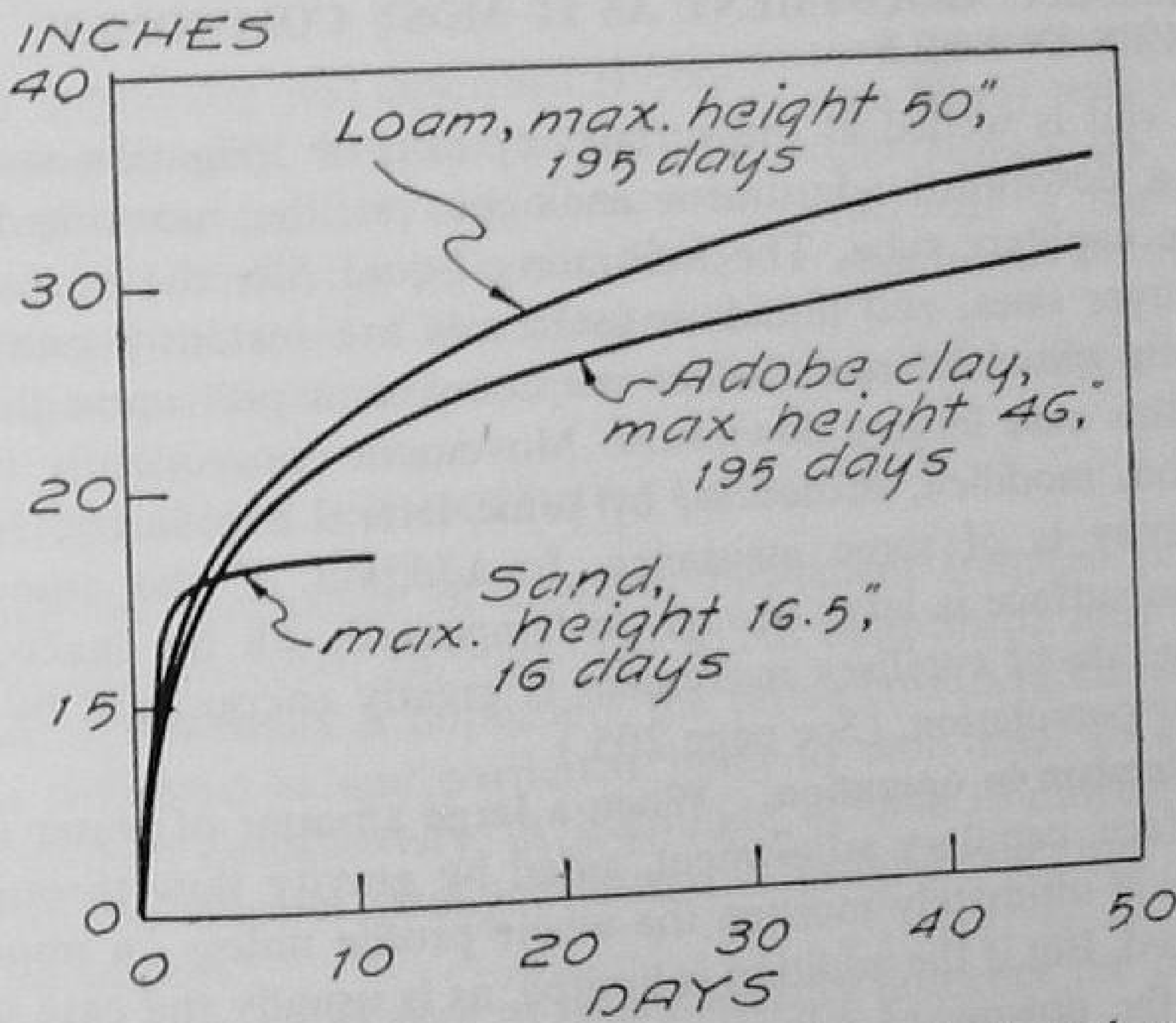

FIG. 7:7. *Upward movement of moisture from a water table through soils of different textures and structures. Note the rapid rise in the sand, but the moderate height attained. Apparently the pores of the loam are more favorable than in the clay, both for a rapid rise and a maximum height. However, the important consideration is the amount of water that can be delivered to a certain point in a unit period of time. (Drawn from data presented by Loughridge.)*

Contrary to popular opinion the type of capillary adjustment just described is not important in field soils except in certain rather special and limited cases. Most arable mineral soils usually are so well drained, either naturally or artifically, as to prevent the internal accumulation of free water for any length of

[18] Loughridge, R. H., "Investigations in Soil Physics; The Capillary Rise of Water in Soils," *Annual Report*, 1892–94, Calif. Agr. Exp. Sta., pp. 91–100.

time. Or if a water table actually does appear within the solum, it is temporary and usually is present at a time of year when it is of no practical consequence. Such a situation, therefore, sharply minimizes the importance of the upward movement of capillary water in the soil from a zone of saturation.

However, in some cases the type of capillary set-up under discussion can be made use of practically. For instance, in poorly drained sandy soils and in peat lands, where the water table at times might be lowered or raised at will, the water level could then be maintained near enough the surface at certain critical times as to provide sub-irrigation by capillarity. Such cases are, however, limited and call for ideal conditions and careful control and are only used for certain crops. This being the situation, let us now turn to a type of capillary adjustment that operates so constantly and universally for the good of higher plants that its mechanism is indispensable.

7:13. CAPILLARY ADJUSTMENT AS IT MOST COMMONLY OCCURS IN SOILS

When a soil is wetted at the surface by rain or irrigation water, the stage is set for a downward adjustment analogous to the movement of moisture in a simple capillary tube. The infiltrating liquid fills the surface interstices, even the larger ones, and liquid-air interfaces are instantly established. Since most of these initial interstitial films are concave, a pull upon the liquid mass occurs, in this case largely downward. Movement consequently takes place in this direction, modified, of course, by some lateral capillarity. Moreover, the pull of gravity is of some assistance. In addition, if the amount of water added at the surface is large enough to temporarily fill the macropores in this vicinity, the rate of capillary movement is greatly encouraged by the bridging effect and by percolation. (See page 205.)

The mechanism in operation. When a large amount of water is received at the soil surface, capillary adjustment, aided by gravity flow through the larger interstices, will ultimately moisten the whole profile unless an impervious layer is encountered. But if the addition is limited, as is usually the case under natural conditions, the downward adjustment will soon become wholly capillary and the penetration will be halted at some point in the soil profile. With a light rain this may be only a few inches below the soil surface. The tension of the water front when equilibrium occurs is in the neighborhood of ⅓ of an atmosphere.

This halt in downward movement takes place, not because the downward capillary pull has become less, but because it is counterbalanced by an upward pull at the upper surfaces of the water mass. Since little free water now is present on top of the soil, liquid-air interfaces of a capillary nature appear in the interstices at and near the soil surface. They are, of course, concave upward and exert a pull in that direction. And if surface evaporation takes place the concavity, and hence the pull, of these films increases rapidly. When this pull equals that of the downward-moving water front, the latter comes to a standstill. (See Fig. 7:8.) And should evaporation or some other phenomenon further

increase the concavity of the upper films, capillarity adjustment might be reversed and the flow directed upward.

This phenomenon of capillary adjustment back and forth according to film tension represents the capillary setup commonly operating in soils. Unlike the capillary adjustment upward from a water table previously described, the movement under discussion may be downward, upward, or lateral. The direction of movement depends on the curvature of the water films at the periphery and in the interior of a given mass of soil water. And what is especially important, the removal of water from any given interstice by increasing the film curvature and hence the pull at this point, initiates a movement in this direction.

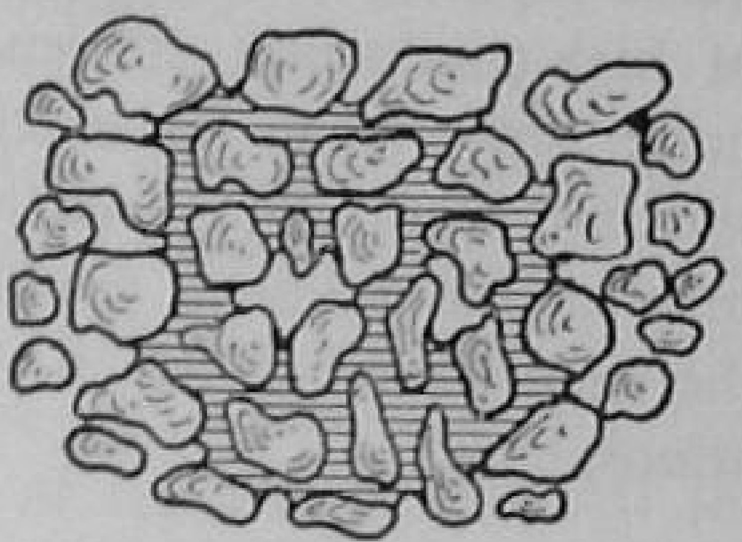

FIG. 7:8. *A body of water, not connected with a water table, at momentary equilibrium in the soil. An increase in film curvature at any point in the system will increase the tension and encourage a capillary adjustment in that direction.*

The type of capillarity just described is continually operating in soils. Yet, due to the dynamic nature of soils, capillary equilibrium is seldom attained. Of all forms of water movement within the soil this type of film adjustment is perhaps of greatest moment in respect to soil conditions and plant growth.

7:14. THE CAPILLARY CONDUCTIVITY OF SOILS

In discussing the mechanics of capillary movement frequent reference has been made to the distances through which the adjustment may take place. While distance undoubtedly is important, the prime consideration is how much water can be delivered at any particular point in unit time. In other words, what is the *capillary conductivity?* A soil might be able to move water a long distance but if the amount finally delivered is insignificant, the phenomenon lacks practical import.

While the texture and structure of soils markedly influence the conduction [19] or efficiency of capillary flow, the fundamental control in any particular case is the difference in capillary tension per unit distance. This may be referred to as the *tension gradient*. If it is high, that is, if the difference in capillary tension between two points a unit distance apart is great, water will adjust toward the higher tension with comparative rapidity. Under comparable conditions, on the other hand, a low gradient means a slower adjustment and consequently a lower delivery. This influence of tension gradient is well illustrated by moisture curves drawn from Gardner and Widtsoe.[20] (See Fig. 7:9.) Here the rate of water movement from a moist soil into a drier one is shown. The higher the per-

[19] Richards, L. A., "Capillary Conductivity Data for Three Soils," *Jour. Amer. Soc. Agron.*, 28: 297–300, 1936.

[20] Gardner, W., and J. A. Widtsoe, "The Movement of Soil Moisture," *Soil Sci.*, 11: 230, 1921.

centage of water in the moist soil, the greater is the tension gradient and the more rapid is the delivery. In this case capillary conductivity obviously is a function of the tension gradient.

But a high-tension gradient is not necessarily enough in itself to insure adequate capillary conductivity. A soil must possess a continuity of capillary pores of high-conduction efficiency and containing enough water to insure rapid liquid flow. When the capillary water is low in amount, it is held within the soil interstices at high energy levels and adjustments even under the urge of high-tension gradients are likely to be sluggish. Such seems to be the case when the energy level at which the soil water is held appreciably exceeds ⅓ of an atmosphere.

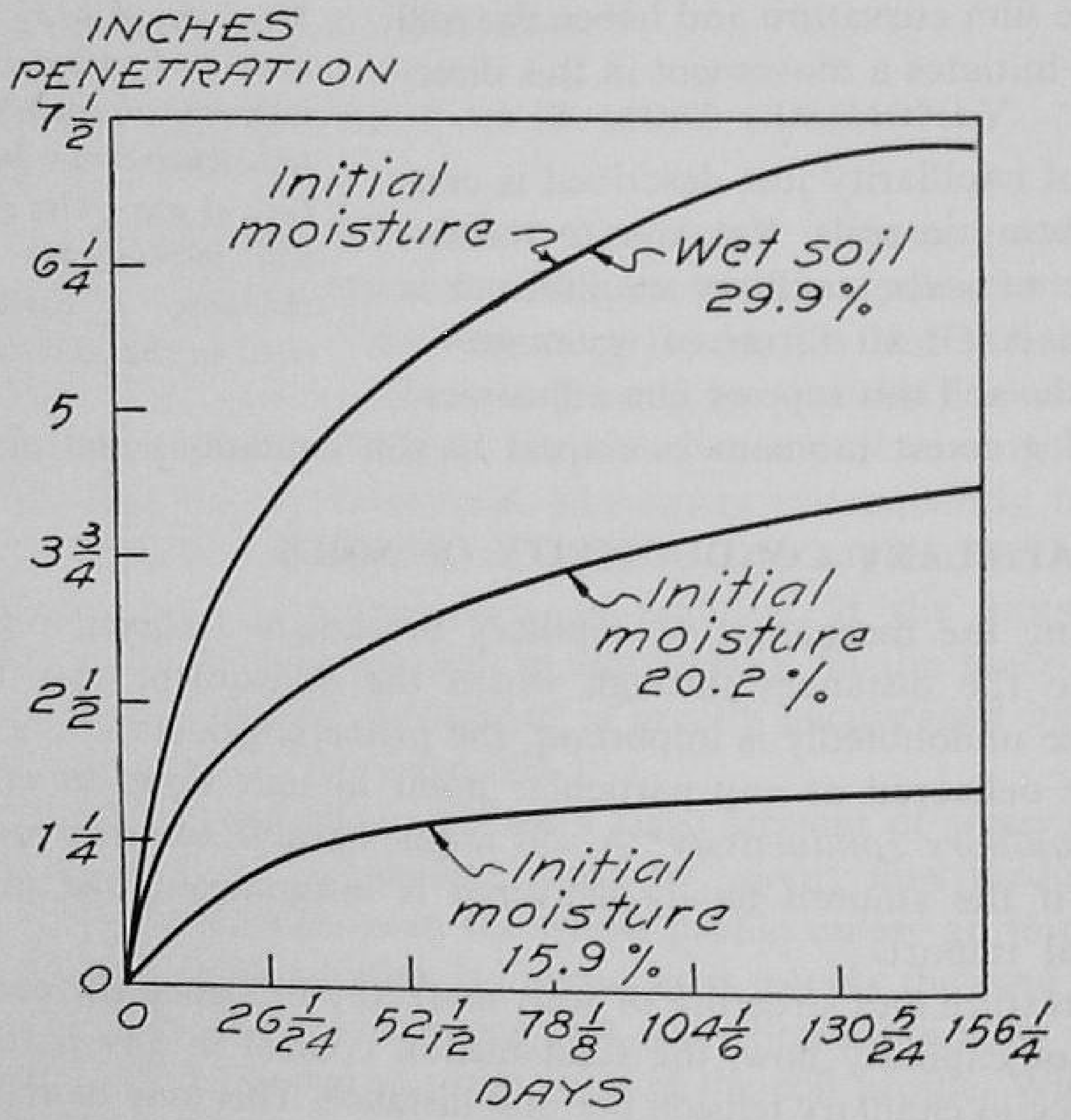

FIG. 7:9. *Curves showing the rate of water movement from a moist soil at three moisture levels to a drier one. The higher the water content of the moist soil, the greater will be the tension gradient and the more rapid will be the delivery. Water adjustment between two slightly moist soils at about the same water content will be exceedingly slow. (After Gardner.)*

This means that a considerable proportion of the so-called capillary water may be more or less immobile, thus imposing a special significance upon the soil water held at tensions extending from about .33 to approximately 0.5 of an atmosphere. Effective capillary conductivity can be expected only from

water within this energy range.[21] The practical significance of capillary conductivity will become more apparent when the evaporation losses of water from soils and the acquisition of moisture by plants are considered.

7:15. GRAVITY FLOW OF WATER THROUGH SOILS—PERCOLATION

When water, either from rain or irrigation, enters the soil it immediately fills the upper-most layer of the macropores. At the same time some of the water is pulled into the contiguous micropores by capillarity. Thus, two types of water movement—percolation (gravity flow) and capillarity—work together in facilitating the irregular downward penetration of the added water. If the water applied is not large in amount, the capillaries surrounding the macropores will suck the latter more or less free of water very soon after infiltration has ceased. Further downward movement of the moisture must continue, if at all, by capillarity. This has already been discussed on page 202.

But if sufficient infiltration of added water occurs, the soil interstices, both micro and macro, ultimately will become more or less filled with water to the full depth of the profile or until an impervious layer is encountered. That this excess water should be removed without too much delay is recognized by everyone. That is, drainage must be instituted and the gravity water cleared from the macropores, especially those of the furrow-slice, before aeration is seriously interfered with and less satisfactory conditions prevail. The mechanism of this removal will now engage our attention.

Percolation described. From what has been said concerning soil porosity, the situation in respect to the drainage setup in a representative mineral soil may be tentatively postulated. Except for cracks, wormholes, and root passages, the larger pores are separated by channels and interstices of capillary size. An individual macropore is somewhat analogous to a glass tube with a constriction near the top and at the bottom. If the tube is filled with water, the rate at which it can be emptied will be controlled in part by the size of the constrictions. Moreover, no movement by gravity will occur unless the weight of a unit water column in the tube is sufficient to overcome the resistance at the constrictions. (See Fig. 7:10, a and b.)

Percolation, except in soils permeated by very large and continuous channels, is a question of overcoming the film tension and friction in a series of restrictions of variable sizes and shapes. Since the macropores are probably con-

[21] In a rough way .33 of an atmosphere of tension represents the transition from capillary to noncapillary pores. At tensions of .33 of an atmosphere and less soil water may move downward by both capillarity and gravity but when the tension is greater than .33 of an atmosphere the adjustment is almost entirely capillary in nature. See Nelson, W. R., and L. D. Baver, "Movement of Water Through Soils in Relation to the Nature of the Pores," *Proc. Soil Sci. Soc. Amer.*, 5: 69–76, 1940; and Browning, G. M., "Relation of Field Capacity to Moisture Equivalent in Soils of West Virginia," *Soil Sci.*, 52: 445–450, 1941.

nected in indefinite vertical series, drainage seems to occur intermittently along irregular and ever-changing vertical courses, depending on the nature of the constrictions. (See Fig. 7:10, c.) Before this can occur, however, the series must be connected with the outer air, both above and below, in such a way as to allow a ready equalization of pressure.

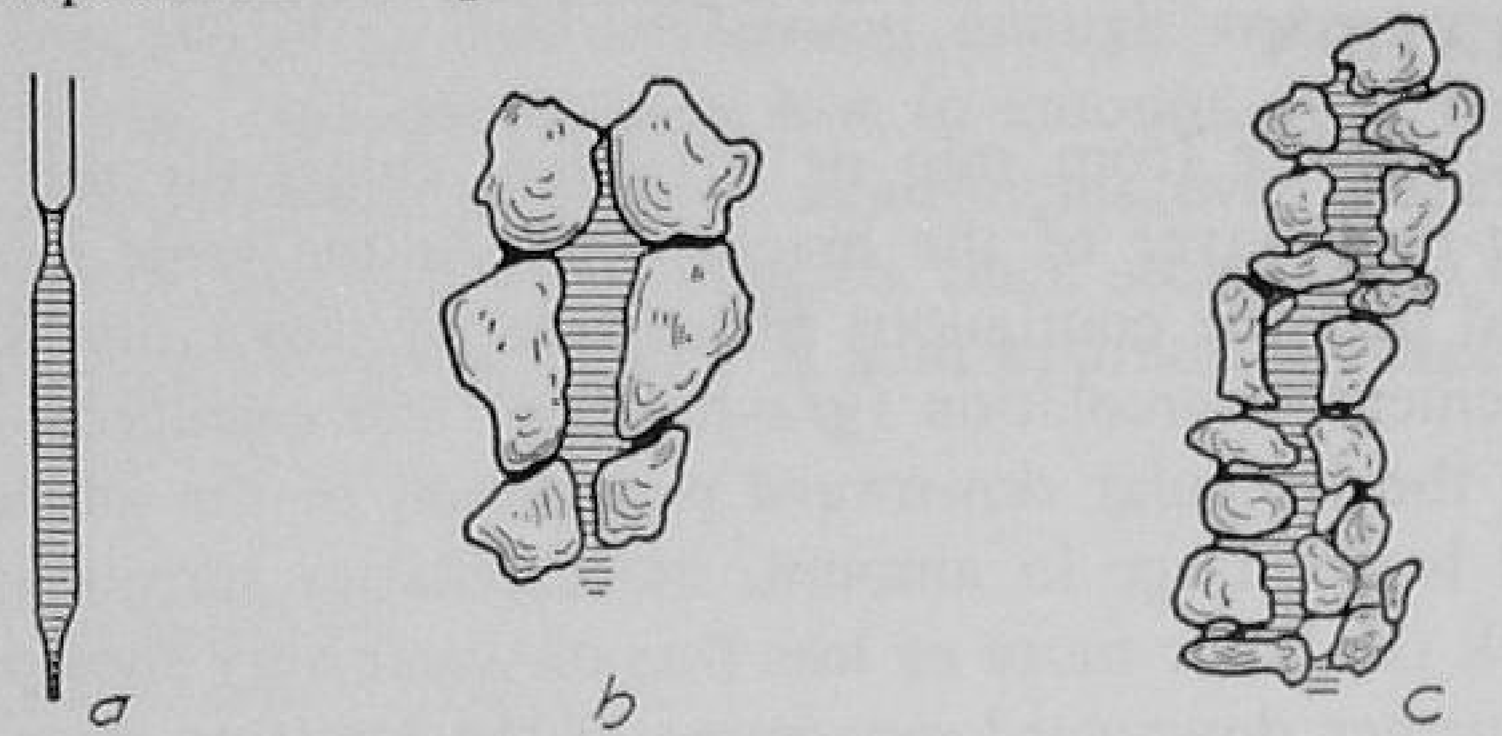

FIG. 7:10. *Obviously the gravity flow of water through a glass tube (a) will be markedly influenced by the constrictions, which might be small enough to prevent ready movement. In (b) an attempt is made to picture the corresponding situation in a soil. In (c) a string of soil macro-pores are shown with their connecting channels. The large pores cannot drain until the resistance at the constrictions is overcome.*

Colloidal swelling and entrapped air. Certain factors undoubtedly further complicate the percolation of water through soils. First, clayey colloidal matter may clog not only the small connecting channels but even the larger macropores. Such colloidal matter may offer little obstruction at first but as it swells it may ultimately nearly close the smaller pores. This is likely to be the case, especially with montmorillonitic clays. Thus, heavy soils that crack during dry weather at first allow rapid percolation of water. Later, however, these cracks may swell shut thus reducing percolation to a minimum.

Secondly, entrapped air, which is sure to be abundantly present in such a complicated system, may also seriously impede the rate of percolation. And finally the whole situation is modified by the irregular occurrence not only of cracks but of wormholes, insect burrows, and decayed root passages.

In general, the finer the texture of the soil, the slower will be the rate of gravitational water flow. In sandy soils the pores are large, the amount of colloidal matter low, and conduction is easy. In heavy soils the pore spaces are small and clogged with colloidal materials and the constrictions are many. Unless granulation is encouraged by organic matter and other means, drainage in such cases will be slow and often rather ineffective. In fact, unless a clayey field soil possesses considerable granulation it may not drain rapidly enough to permit agricultural operations sufficiently early in the spring or soon enough after a heavy rain later in the season.

7:16. VAPOR-LIQUID EQUILIBRIUM FUNDAMENTALS

Water vaporization as it relates to soils may be distinguished for convenience of discussion as *internal* and *external*. In the one case the change from the

liquid to the vapor state takes place within the soil, that is, in the interstices, mostly those of macro- and semimicro-size. In the second case the phenomenon occurs at the land surface and the resulting vapor is lost to the atmosphere by diffusion and convection. The latter commonly is spoken of as *surface evaporation* and will be considered later (page 224). For the present only vaporization and vapor adjustment tendencies *within* the soil are pertinent. But first let us review a few water vapor fundamentals.

Where a free water surface is in contact with air, equalization tends to occur, water molecules moving from the liquid to the air and from the air back to the liquid. As long as the air is unsaturated and temperature differences do not interfere, the movement of water molecules into the air is the faster, and the liquid phase is reduced. This is evaporation.

However, if this phenomenon occurs in a closed system, as would be more or less the case within the soil, the movements in the two directions soon become equal and a state of equilibrium is established. Under this condition the air becomes saturated, that is, the relative humidity soon is near 100 per cent. Since the liquid phase is not now subject to reduction, evaporation is said to have ceased. The system is in dynamic equilibrium.

Now if the temperature of the system should be raised, the capacity of the air for water vapor would increase and evaporation would again occur. But if the temperature of the system should be lowered, the capacity of the air for vapor would be decreased. Condensation, that is, a faster return of molecules to the liquid than the outgo therefrom, would take place. There are thus three possibilities in respect to the interrelations of a liquid and its vapor—evaporation, dynamic equilibrium and condensation.

The water vapor maintained in the air by the interchanges just referred to exerts a pressure called *vapor pressure* or aqueous tension. At any given temperature it is at a maximum when the air is saturated and declines as the relative humidity grows less. Also the vapor pressure of a liquid varies with temperature, the pressure at a given relative humidity rising with the temperature of the system. This is due to the increasing ease with which molecules leave the liquid surface. So much for fundamentals. What about soil applications?

7:17. RELATIVE HUMIDITY OF THE SOIL AIR AND WATER VAPOR ADJUSTMENTS THEREIN

Within the soil the atmosphere, due to the equalization tendencies already explained, is held at or very near the saturation point as long as the moisture content is not below that of the hygroscopic coefficient. At this tension (31 atmospheres) and less, water seems to be free enough molecularly to maintain the air at approximately 100 per cent relative humidity (at ordinary temperatures about 98 per cent at the hygroscopic coefficient). But when the soil moisture drops below the hygroscopic coefficient, and consequently is held with a greater tenacity, water vaporizes with greater and greater difficulty and its vapor pressure becomes lower and lower. At 10,000 atmospheres of negative pressure

the aqueous tension is practically zero. See Fig. 7:11 for a graphic representation of these phases.

This maintenance of the soil air at or very near a relative humidity of 100 per cent is of tremendous importance especially in respect to biological activities. This is perhaps the most important single feature in respect to the vapor-liquid interrelations within soils. It is a truism that should always be kept in mind. Nevertheless, the actual amount of water present in the vapor form in a soil at optimum moisture is surprisingly small being, at any one time, perhaps not over 10 pounds to the acre-furrow slice.

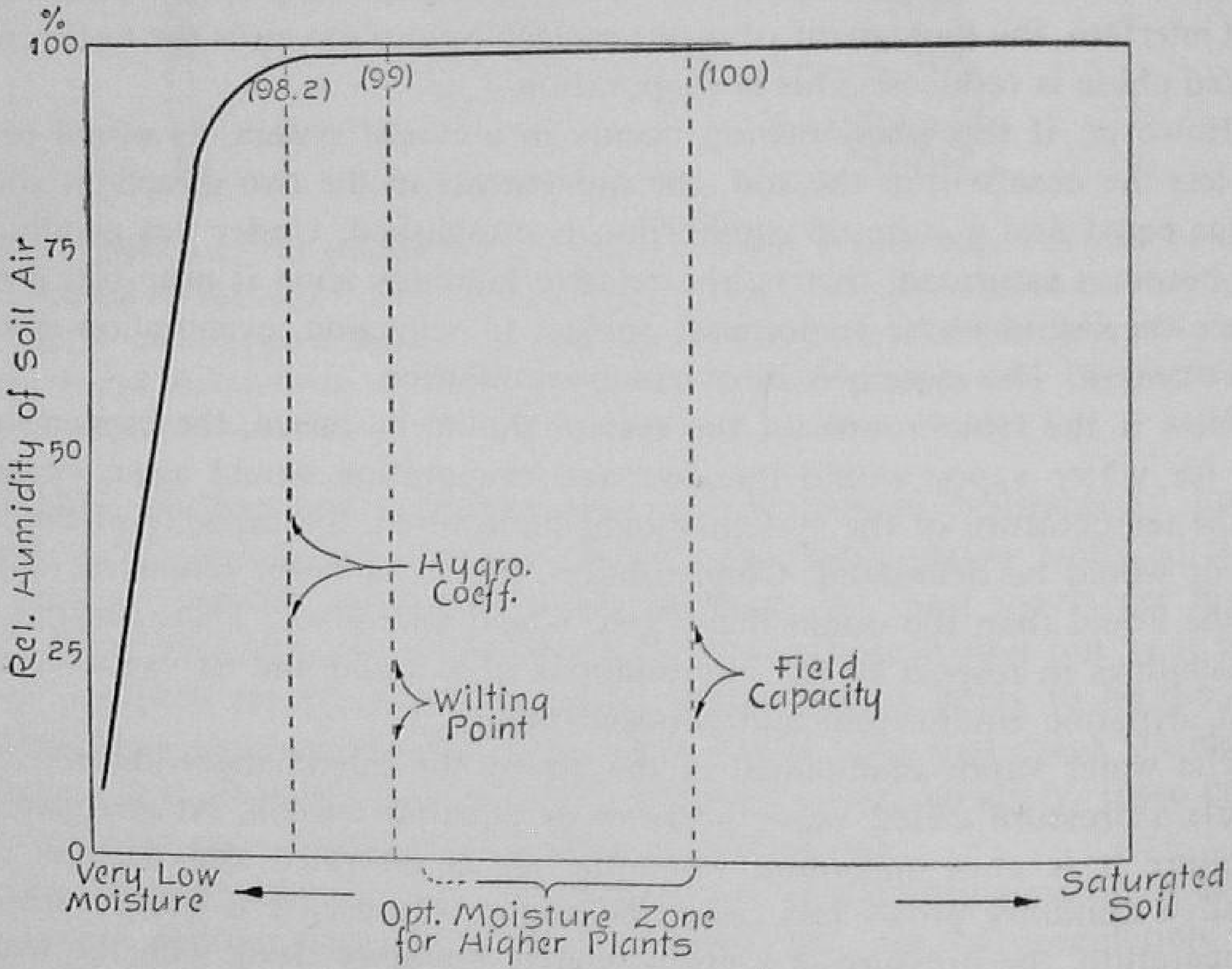

FIG. 7:11. *Relative humidity of soil air (in percentage) at various moisture contents, the temperature being suitable for higher plants. Note that when soil moisture is at optimum for plant growth, the soil air is practically saturated with water vapor.*

Water vapor movement. Now what about the movement of water vapor in the soil—that is, from one interstice to another? And if such a tendency exists, what are the forces involved and how extensive is the adjustment, especially when moisture conditions are optimum for higher plants? Let us deal with the mechanics first.

Undoubtedly a diffusion of water vapor from one water free interstice to another and from one horizon to the contiguous one does tend to occur. The motive force is due to differences in vapor pressure, the adjustment tendencies being from points of high aqueous tension to those that are lower. That is, a *vapor-pressure gradient* [22] is operative. Thus, if a moist soil where the vapor

[22] A *vapor-pressure gradient* is simply the difference in vapor pressure of two

pressure is high is in contact with an air-dry layer where the aqueous tension is lower, a diffusion into the drier area will tend to occur. Likewise, if the temperature of one part of a homogeneously moist soil mass is lowered, water vapor will tend to move in this direction due to the lowered vapor pressure. Heating will have the opposite effect.

The two soil conditions mentioned above—differences in relative humidity and in temperature—seem to set the stage for the movement of water vapor under ordinary field conditions. However, they may work at cross purposes and reduce vapor transfer tendencies to a minimum or they may be so coordinated as to raise them to a maximum. The possible situation is set forth in Fig. 7:12. In the first case (a) the equilibrium tendencies more or less negate each other. But in the second case (b) differences in the temperature and moisture of the two soil layers are such as to maintain vapor-pressure differences and thus the possibility of vapor transfer will be greatly enhanced.

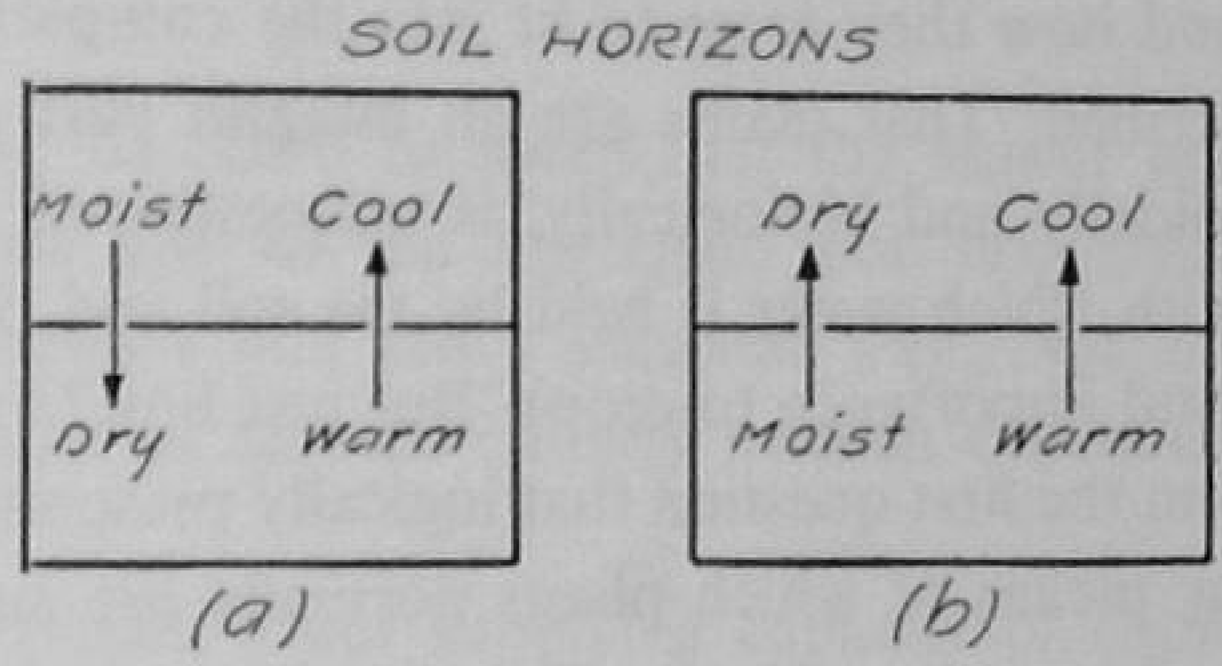

FIG. 7:12. *Diagram indicating the vapor movement tendencies that may be expected between soil horizons differing as to temperature and moisture. In (a) the tendencies more or less negate each other; but in (b) they are coordinated and considerable vapor transfer might be possible if the liquid water in the soil capillaries does not interfere.*

Undoubtedly some vapor transfer does occur within soils. The extent of the movement by this means, however, even from one contiguous macro pore to another, probably is not great, especially if the soil water is within the range optimum for higher plants.

The reasons for this are fairly obvious. As already suggested, the soil air, if moisture relations are satisfactory for plants, is practically always saturated with water vapor. (See Fig. 7:11.) Hence an appreciable vapor-pressure gradient due to a difference in relative humidity is improbable. And even though differences in temperature should create a very definite vapor-pressure gradient, the movement would be more or less blocked by the water occupying the capillary channels connecting the air pockets. Hence, vapor diffusion back and forth within the soil probably is of no particular importance in humid regions except in special cases. With aridic or semi-aridic regions or where a rainy season alternates with a long dry spell, appreciable water vapor transfers might take place.[23] How extensive or how important such a diffusion actually is cannot be stated at present.

points a unit distance apart. The greater this difference, the more rapid diffusion tends to become and the greater is the transfer of vapor water during a unit period.

[23] Lebedeff, A. F., "The Movement of Ground and Soil Waters," *Proc. Internat. Congress Soil Sci.*, 1: 459–494, 1927.

See also Smith, W. O., "Thermal Conductivities in Moist Soils," *Proc. Soil Sci. Soc. Amer.*, 4: 32–40, 1939.

Such a conclusion leaves the stress, as far as vapor-liquid equilibria are concerned, upon the relative humidity of the soil air and upon the fact that when the soil moisture is satisfactory for higher plants the atmosphere of the soil is saturated, or nearly so, with water vapor.

7:18. HOW PLANTS ARE SUPPLIED WITH WATER—CAPILLARITY AND ROOT EXTENSION

In preceding discussions reference is frequently made to higher plants and how they seem to fit into the complex and dynamic water system described. That plants are an integral part of the moisture cycle, both colloidally and biologically, is unquestioned. Undoubtedly, also, the tenacity with which water is held by the soil and the ease of its adjustments are of vital importance to crops. But just how? In the consideration of this problem the first question that logically presents itself is, what are the mechanics by means of which plants normally are supplied with soil water?

At any one time only a small proportion of the soil water lies in the immediate neighborhood of the adsorptive surfaces of plant root systems. Consequently, a query arises as to how the immense amount of water (see page 223) necessary to offset transpiration is so readily and steadily acquired by vigorously growing crops. Two phenomena seem to make adequate and continuous contact possible if the soil is in good condition for the plant growth: (1) the capillary adjustment of the soil water and (2) the extension of the root system of plants, especially when the elongation is rapid.

Rate of capillary movement. When plant rootlets begin to absorb water at any particular point or locality in a moist soil, the thick water films at the capillary fronts are thinned and their curvatures increased. This intensifies the capillary pull in this direction and water tends to move toward the points of plant absorption. The rate of movement depends on the magnitude of the tension gradients developed and the conductivity of the soil interstices. A full explanation of this truism is offered on page 203.

With some soils the above adjustment may be comparatively rapid and the flow appreciable; in others, especially heavy and poorly granulated clays, the movement will be sluggish and the amount of water delivered meager. Thus, a root hair, by absorbing some of the moisture with which it is in contact, automatically creates a tension gradient and a flow of water is initiated toward its active interfaces.

How effective the above flow may be under field conditions is questionable. Many of the early investigators greatly overestimated the distances

through which capillarity may be effective in satisfactorily supplying plants with moisture. They did not realize that the rate of water supply is the essential factor and that capillary delivery over appreciable distances is very slow. Plants must have large amounts of water regularly and rapidly delivered. Therefore, capillarity, although it may act through a distance of a foot or two, if time be given, may actually be of importance through only a few centimeters as far as the hour by hour needs of plants are concerned.[24]

The above statement must not be taken to mean that the slower and long-ranged capillary adjustments are in the aggregate not important. They are important but in a broader and more seasonal way. Nor are gravitational and vapor transfers to be ignored entirely even in this hour-by-hour watering of plants.

Rate of root extension. This limited water supplying capacity of capillarity directs our attention even more forcibly to the rate of root extension and here early workers made an underestimate. They failed to recognize the rapidity with which root systems expand and the extent to which new contacts are constantly established. (See Fig. 5:4.) During favorable growing periods, roots often elongate so rapidly that satisfactory moisture contacts are maintained even with a lessening water supply and without any great aid from capillarity. The mat of roots, rootlets, and root hairs in a meadow, between corn or potato rows, or under oats or wheat is ample evidence of the minutiae of the ramifications.[25]

The rate of root extension is surprising even to those engaged in plant

[24] Miller, E. C., "Comparative Study of the Root System and Leaf Areas of Corn and Sorghums," *Jour. Agr. Res.*, 6: 311–331, 1916.

Keen, B. A., "The Limited Role of Capillarity in Supplying Water to Plant Roots," *Proc. and Papers, First Internat. Cong. Soil Sci.*, 1: 504–511, 1927.

See also Bouyoucos, G. J., "Capillary Rise of Moisture in Soil under Field Conditions as Studied by the Electrical Resistance of Plaster Paris Blocks," *Soil Sci.*, 64: 71–81, 1947.

[25] Dittmer, H. J., "A Comparative Study of the Subterranean Members of Three Field Grasses," *Science*, N. S., 88: 482, 1938.

Dittmer reports as follows regarding the roots and root hairs in 1 cu. in. of soil:

Plant	*Number of Roots*	*Number of Root Hairs*	*Combined Length, Feet*	*Combined Surface, Square Inches*
Oats	110	150,000	630	15
Rye	150	300,000	1,300	30
Ky. bluegrass	2,000	1,000,000	4,000	65

See also Dittmer, H. J., "A Quantitative Study of the Roots and Root Hairs of a Winter Rye Plant," *Amer. Jour. Bot.* 24: 417–420, 1927.

productions. On the basis of the data available the elongation may be rapid enough [26] to take care of practically all of the water needs of a plant growing in a soil at optimum moisture. If this be the case, the plant is more or less independent of capillary adjustment for its immediate water supply.

It is also to be noted that if capillary movement is of little import when the water films are thick, such an adjustment can be counted out almost entirely when the water held in the interstices is depleted and capillarity becomes still more sluggish. This, however, in no way minimizes the importance of capillarity in other cases such as the infiltration of water and its downward movement in the soil. The upward adjustment of moisture in response to evaporation at land surfaces and equalizations laterally where rate is not an especially vital factor are other cases in point.

7:19. WILTING COEFFICIENT (CRITICAL MOISTURE)—A SECOND IMPORTANT PLANT CONSIDERATION

As long as the force with which soil water is held is comparatively low, that is, in the tension range centering around .5 of an atmosphere, a vigorously growing plant should have little difficulty in obtaining water rapidly enough to offset transpiration. Its roots are ever pushing into moisture loosely held and absorption should be easy. In addition, capillary conductivity should bring in some low-energy water from neighboring zones.

But, if the root zone receives no new supply of water, a different condition soon develops. As the moisture of the soil is gradually reduced by surface evaporation and plant absorption, the water remaining is held with ever-increasing tenacity. Absorption by the plant becomes more and more difficult against the higher and higher tensions. At first the plant is able to adjust to the diminished intake. Soon, however, the tension is such that the absorption by the plant will barely meet its transpiration losses. Obviously if water is not applied at this critical stage the plant will wilt, at first temporarily,[27] then permanently. And the phenomenon occurs not because the plant is absorbing no water but because the intake, due to the high negative tension of the soil moisture, is too slow to offset tran-

[26] Kramer, P. J., and T. S. Coile, "An Estimation of the Volume of Water Made Available by Root Extension," *Plant Physiol.*, 15: 743–747, 1940.

[27] Vigorously growing plants in the field often show wilting during the hotter part of the day but recover toward evening. This is commonly observed with corn, the leaves rolling in a characteristic way. As one might surmise, this temporary phenomenon is not due to a low water content of the soil but is caused by an abnormally high rate of transpiration. It usually does little harm.

spiration. The percentage of moisture within the zone of influence of the plant roots when permanent wilting first occurs is called the *wilting coefficient* or the *critical moisture* point.[28]

The wilting coefficient is usually determined under controlled conditions in a greenhouse, using seedlings such as sunflower or some grain such as wheat or rye. The extended work of Briggs and Schantz[29] indicates that the permanent wilting point thus determined is practically the same for all plants growing on the same soil.[30] While this conclusion is open to certain criticisms,[31] it nevertheless seems more or less accurate. If such is the case, the phenomenon can be accounted for only by the fact that the soil forces, in their effect on the entrance of water into the plant, are so powerful as to override any distinguishing characteristics that plants may possess in respect to moisture absorption, or at least to reduce such differences within the error of actual experimentation.

Since the wilting of a plant is determined in large degree by the tenacity with which the soil water is held, it is to be expected that this biological phenomenon, conditions being comparable, will occur at about the same

[28] This term applies especially to humid-region plants. Desert plants, able to reduce their transpiration to a very low magnitude or even capable of storing water in special tissues, do not have a critical moisture in the sense used here.

[29] Briggs and Schantz in their investigations used glass tumblers holding about 250 cc. of soil in an optimum condition. The seeds were placed in this soil, after which soft paraffin was poured over the surface in order to stop evaporation. The seedlings on germination were able to push through this paraffin and to deplete the underlying soil of moisture.

When definite wilting occurred as determined in a saturated atmosphere, a moisture determination was made on the soil. The resulting figure, expressed as percentage of moisture based on dry soil, represents the wilting coefficient for the soil used.

Briggs, L. J., and H. L. Schantz, *The Wilting Coefficient for Different Plants and Its Indirect Determination,* Bulletin 230, Bureau of Plant Industry, U. S. Dept. of Agriculture, 26–33, 1912. See also Richards, L. A., "Fifteen Atmosphere Percentage as Related to Permanent Wilting Percentage," *Soil Sci.,* 56: 331–339, 1943; and Veihmeyer, F. J., and A. H. Hendrickson, "Methods of Measuring Field Capacity and Permanent Wilting Percentage of Soils," *Soil Sci.,* 68: 75–94, 1949.

A new procedure for the determination of the wilting coefficient has been proposed by Breazeale, Edward, and W. T. McGeorge, "A New Technic for Determining Wilting Percentage of Soil," *Soil Sci.,* 68: 371–374, 1949.

[30] It must not be inferred from this conclusion that all plants have the same drought resistance. With humid-region plants, root spread is by far the most important factor in this regard. Plants with the more extended root systems are, of course, able to draw on a greater amount of water and better withstand a drought period. Moreover, some plants can reduce their transpiration to a surprising degree, thus satisfactorily meeting the lessened intake of water. Desert species are good examples.

[31] Caldwell, J. S., "The Relation of Environmental Conditions to the Phenomena of Permanent Wilting in Plants," *Physiological Researches,* U. S. Dept. of Agriculture. Vol. I, No. 1, 1913.

moisture tension for every normal soil. Experimental results show the wilting coefficient to be at about 15 atmospheres of negative pressure, the figure ranging a little higher for sandy soils than for those of a heavy texture.[32] This means that humid-region plants cannot absorb water freely enough against such a pressure to satisfactorily offset transpiration losses. Obviously the *wilting coefficient* (about 15 atmospheres) is located between the *hygroscopic coefficient* (approximately 31 atmospheres) and the *field capacity* (about ⅓ of an atmosphere) and is definitely in the zone of very sluggish capillarity.[33] (See Figs. 7:13 and 7:14.)

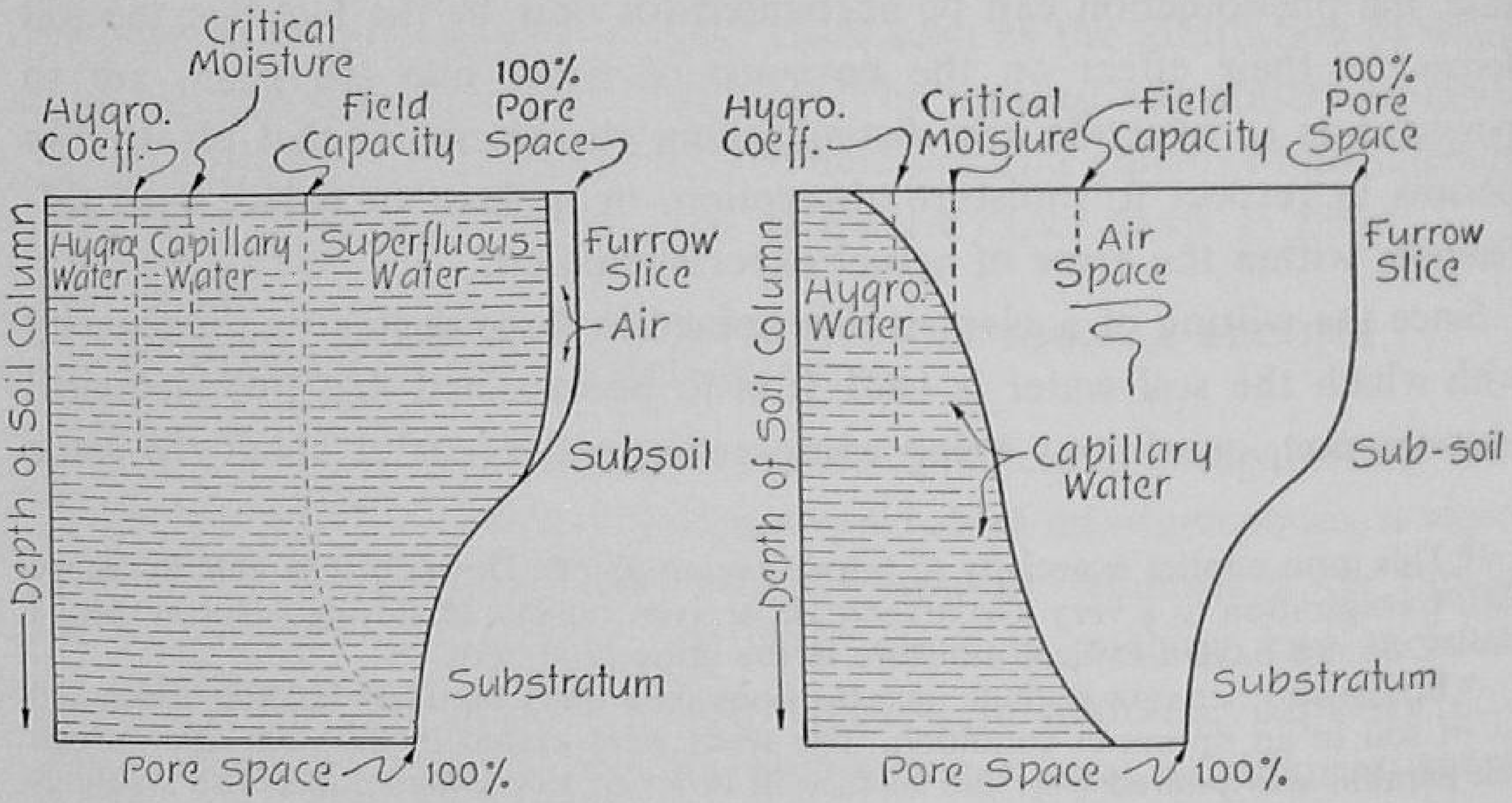

FIG. 7:13. *The diagram at the left represents a soil profile practically saturated with water. But if good drainage is established such a soil will soon present moisture and air conditions optimum for plants. (See Fig. 7:5, page 196.)*

The profile at the right is markedly depleted of moisture. The first few inches of soil are very dry and practically no available water remains in the furrow slice. Shallow rooted crops would suffer severely during such a dry spell. Deep rooted plants, on the other hand, would continue to thrive because of the available water in the subsoil.

[32] Russell, M. B., "Soil Moisture Sorption Curves for Four Iowa Soils," *Proc. Soil Sci. Soc. Amer.*, 4: 51–54, 1939.

[33] After studying the relationships of the wilting coefficient to other soil conditions, Briggs and Schantz suggested the following formulae for the calculation of the wilting coefficient:

$$\text{Wilting coeff.} = \frac{\text{Hygro. coeff.}}{.68}$$

$$\text{Wilting coeff.} = \frac{\text{Moisture equiv.}}{1.84}$$

Briggs, L. J., and H. L. Schantz, *The Wilting Coefficient for Different Plants and Its Indirect Determination*, Bulletin 230, Bureau of Plant Industry, U. S. Dept. of Agriculture, 65, 1912.

While the mathematical relationships suggested above hold fairly well for averages

It is evident that the wilting coefficient of field soils will be influenced by a number of conditions. Important among these are soil texture and the percentage of organic matter present. Their influence is best shown when moisture is expressed in percentage. In general the wilting coefficient will range from 2 to 3 per cent in the case of a sand to as high as 15 or 20 per cent with a heavy clay containing a large amount of humus. Peat soils with an organic content of 80 per cent will often show a critical moisture in the neighborhood of 100 per cent.

7:20. THE BIOLOGICAL CLASSIFICATION OF SOIL-WATER—FURTHER PLANT RELATIONSHIPS

From the discussions already presented, it is evident that not all moisture present is available or suitable for the rapid vegetative growth of a plant. Three tentative divisions of the soil water may be made on this basis: *unavailable, desirably available,* and *superfluous.* (See Fig. 7:14.)

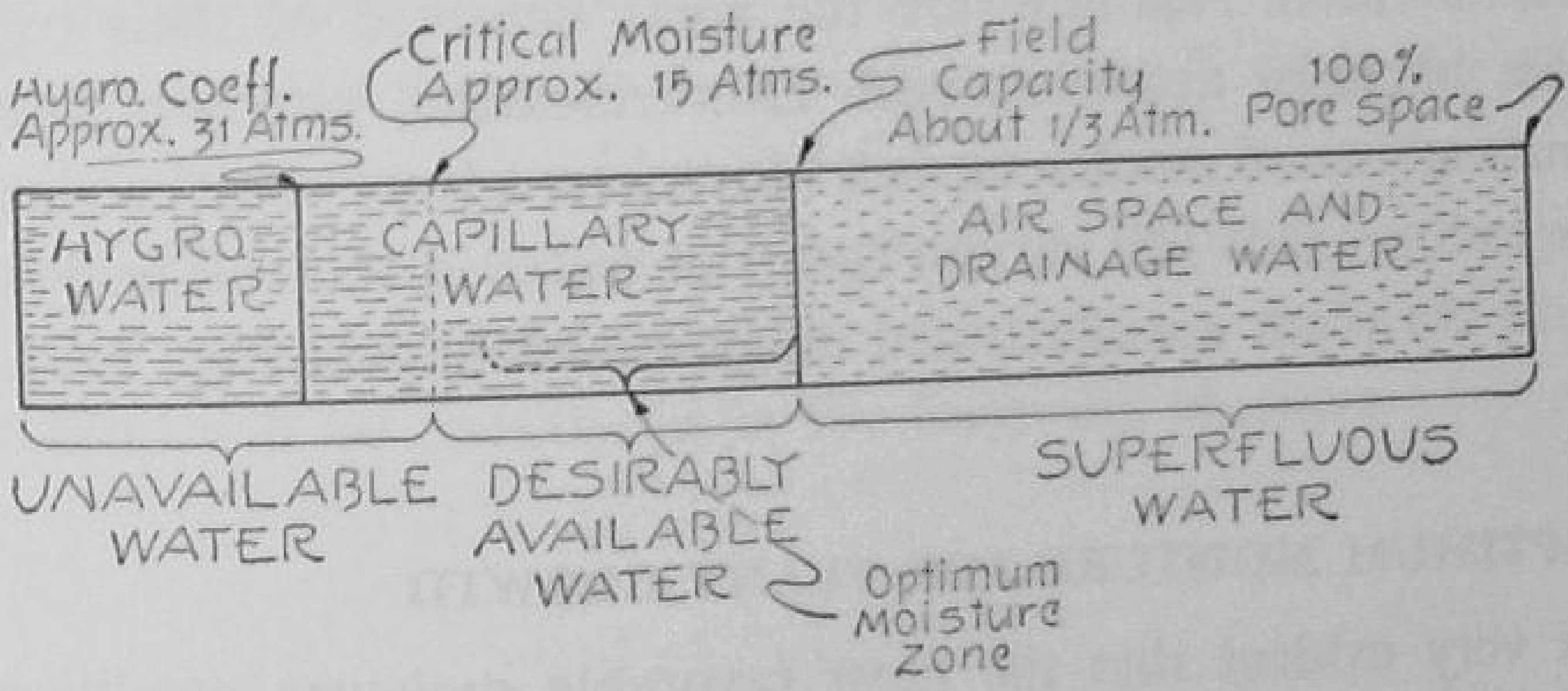

FIG. 7:14. *Diagram showing the relationship of the various forms of soil moisture to higher plants. By inserting the critical moisture point (wilting coefficient), the physical classification of soil water can be converted into a biological classification and the plant significance of moisture tensions and adjustments graphically pictured.*

It is obvious that all of the water below the wilting coefficient is out of reach of plants as far as normal vegetative growth is concerned. For this reason it is termed *unavailable* although it is, in fact, not entirely so. Such water includes all of the hygroscopic and that part of the capillary which is so tightly held as to be absorbed too slowly to meet the needs of plants in a vigorous vegetative condition.

In rating the exceedingly sluggish capillary water, sometimes called the *inner-capillary,* as unavailable, some reservations should be made. Under

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based on large numbers of samples, the correlations for individual soils may show wide deviations.

certain conditions plants, especially those adapted to arid regions, are thought by some to reduce the soil water almost to the hygroscopic coefficient.[34] Also roots imbedded in the soil colloidal matter probably make some use of such capillary water. Again bacteria and fungi growing on the viscous colloidal complexes probably employ such moisture advantageously. Moreover, plants in a dormant condition on a dry soil may find this very tightly held capillary moisture of some value.

If water is now added to the soil in abundance, that moisture between the critical moisture zone to about the field capacity may ordinarily be considered as *desirably available* for the vegetative use of higher plants. However, when too much free water is present, conditions detrimental to growth are encouraged, the situation becoming more adverse as the saturation point is approached. The gravitational water is, therefore, designated as *superfluous*. (See Fig. 7:14.)

The unfavorable effects of such moisture on the plant arise largely from the poor aeration. Not only are the roots deprived of their oxygen, but favorable bacterial activities, such as nitrification, nitrogen fixation, and ammonification, are much retarded. Moreover, adverse biochemical changes may be encouraged. The various forms of water in the soil and their availability to the plant are illustrated diagrammatically in Fig. 7:14. Study it closely.

7:21. OPTIMUM MOISTURE FOR PLANT GROWTH

It is very evident that the most favorable moisture condition for the growth of higher plants, and also for most microorganisms as well, occurs in a soil when moisture is present in large enough amounts to be at a fairly low negative tension. Such an optimum is not found at any definite percentage of water but exists between limits or as a zone, beginning somewhat above the critical moisture point and extending outward to about the field capacity. (See Fig. 7:14.)

It is thus apparent that the soil may undergo the fluctuation in moisture content suggested and yet plants will grow normally. In fact, the fluctuations in the soil moisture that constantly occur under field conditions may favorably affect aeration, resulting in a stimulating influence on plant growth that would be absent if the water content were kept constant. An over-all idea as to the possible fluctuations of soil moisture, from soil saturation to

[34] Alway, F. J., *Studies on the Relation of the Non-Available Water of the Soil to the Hygroscopic Coefficient*, Research Bulletin 3, Nebr. Agr. Exp. Sta., 1913.

drought, and the effects upon aeration, may be obtained by comparing the three diagrams of Figs. 7:5 and 7:13.

Granulation has considerable influence on the extent of the optimum moisture zone. The more suitable the granulation, the better able is the plant to accommodate itself to changes in water content without a disturbance of normal growth. Drainage, liming, addition of organic matter, and tillage, by leading up to such a condition, increase the effectiveness and economy of soil-moisture utilization. During the growing season the prime concern of the farmer usually is soil moisture.

The important problem, therefore, is to keep the moisture of the soil somewhere within the optimum zone. After excessive rainfall, conditions should be such as to allow the presence of gravitational water in the soil for only a brief time. This means adequate underdrainage to remove quickly most of the excess water, especially that of the furrow slice.

Proper soil management also includes arrangements whereby surface runoff may be disposed of with little erosion damage. The maintenance of optimum water also demands conservation methods in so far as they are effective, supplemented in arid and semi-arid regions by irrigation. Thus the success of all fertility treatments depends in the end on the proper management of the water of the soil. The various phases of moisture regulation and control will be considered in the following chapters.

CHAPTER

8

Vapor Losses of Soil Moisture and Their Regulation

WHILE THE ultimate objective in the field control of soil water is the maintenance of an optimum moisture condition for plants, there are many factors and phases involved. In order to obtain a clear insight into the situation, it is advisable first to consider what happens when precipitation and irrigation water are received and utilized and the extent to which deflections and later losses may occur.

8:1. TYPES OF WATER LOSS FROM SOILS

The various ways by which moisture is lost from soils both before and after infiltration may be grouped for convenience of discussion under two very general heads: (1) *vapor* losses and (2) losses in *liquid* form. The situation is presented in diagrammatic form in Figure 8:1 in which the individual losses are shown in their proper positions. Since this sketch will be used as a basis for further discussion, its visualization, at least in a general way, will be found worth while.

Because of the complexities involved, each form of loss, its significance, and to some extent its control will be considered separately. Other phases relating to the crop utilization of soil moisture will be discussed as occasion arises. Finally the major ideas relative to soil moisture control will be drawn together in order that the general concept may not be lost in the maze of detail.

On the basis of both logic and convenience the vapor losses will be disposed of first, leaving the liquid removals for a succeeding chapter (Chapter 9). But before beginning such a consideration, a generalization that should be kept in mind constantly will be emphasized. Vapor losses from soils are subject to no appreciable practical control except in special cases. In fact,

one vapor loss, that of transpiration by crops, is deliberately enhanced by promoting increased crop yields, an objective that most farmers strive to attain.

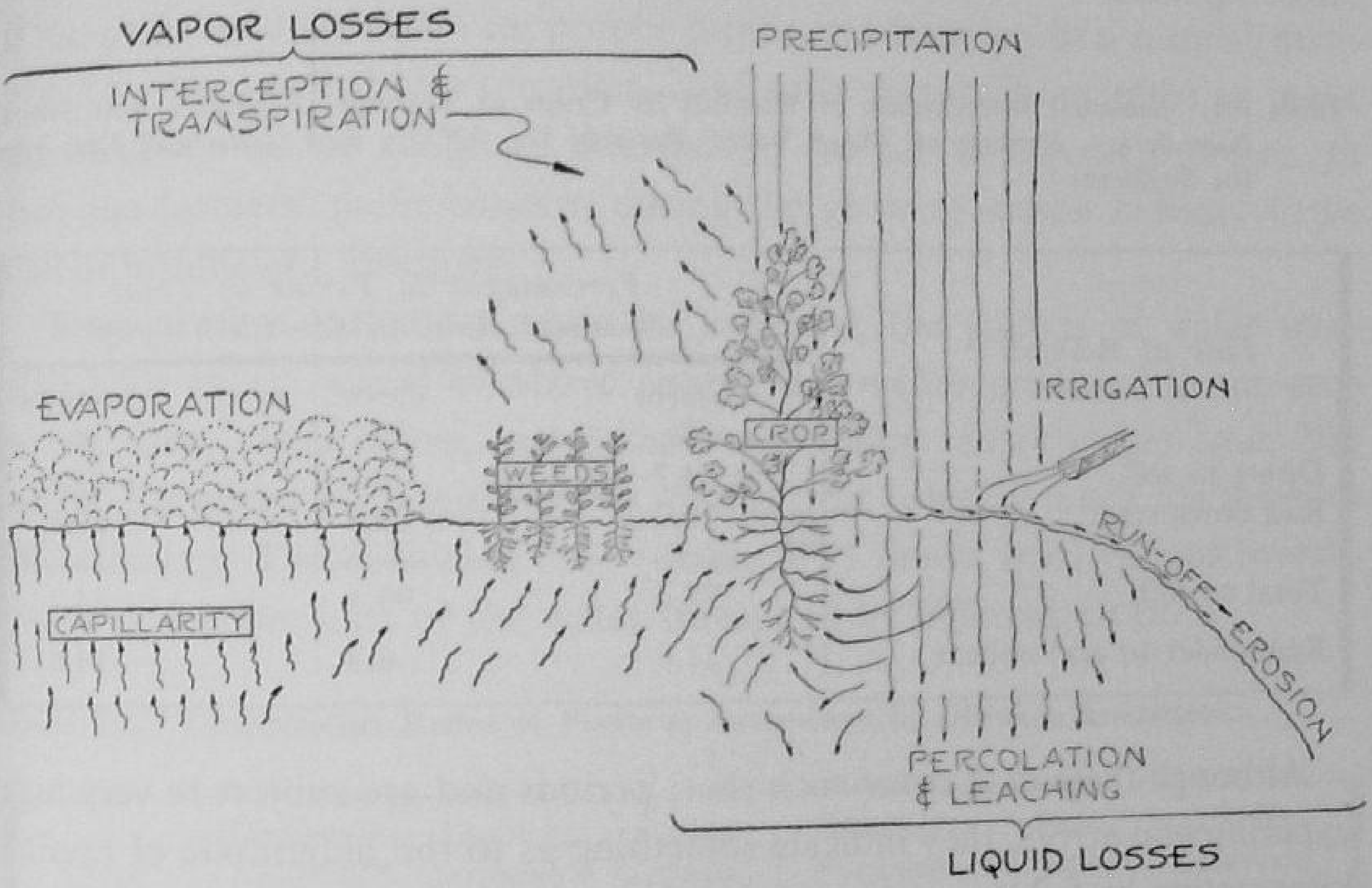

FIG. 8:1. *Diagram showing the various ways by which water may be lost from soils. In practice more control can be exerted over liquid losses than over those of vaporization. Note that the latter entails only a loss of water, while in the case of drainage and runoff, losses of nutrients are also involved. Runoff often results in serious erosion in addition.*

8:2. INTERCEPTION OF RAIN WATER BY PLANTS

Rainfall data are often dealt with as though precipitation ordinarily reaches the soil in its entirety. Such is far from the case as a person must realize when he considers the intercepting capacity of the vegetative cover, especially that presented by a dense forest. The degree to which rain is thus caught and returned to the air by evaporation is surprisingly large.

In general, the lower the rainfall the greater is the percentage diversion by the vegetative cover. And as might be expected, the proportionate loss is markedly higher when the rain is received in light showers. Such precipitation is often entirely lost as far as the soil is concerned. Forests in humid temperate regions divert on the average perhaps 25 per cent of the yearly precipitation, allowing less than 5 per cent to run down the limbs and trunks into the soil.[1]

[1] See Horton, R. E., "Rain Interception," *Monthly Weather Review*, 47: 603–623, 1919. See also Zon, Raphael, "Forests and Water in the Light of Scientific Investiga-

Surprisingly enough the influence of field crops, during the season that they occupy the soil, may approach that of forests in many cases. The yearly interception is, of course, much less. The figures in Table 8:1 are most significant.

Table 8:1. Seasonal Interception of Rainfall by Crops at Bethany, Missouri, and Sussex, New Jersey. Average of Three Years' Records for Alfalfa and Corn and One Year for Soybeans [2]

Fate of Rainfall	*Percentages in Terms of Total Seasonal Rainfall for Each Crop*		
	Alfalfa %	*Corn* %	*Soybean* %
Direct to soil	64.7	70.3	65.0
Ran down stem	13.7	22.8	20.4
Total to soil	78.4	93.1	85.4
Remainder to atmosphere	21.6	6.9	14.6

Although these data cover such short periods and are subject to very high experimental errors, they indicate something as to the magnitude of rainfall interception by field crops. In general, it may be safe to conclude that from 5 to perhaps 20 per cent of the seasonal rainfall of humid temperate regions will be caught and returned to the atmosphere by ordinary field crops, the magnitude in any particular case depending in part on the kind, vigor, and stage of maturity of the crop occupying the land. Of a seasonal rainfall of 15 inches, for instance, only 12 to 14 inches might finally reach the soil, to say nothing of the inequality of the distribution in the soil due to the passage down the stems. While interception losses undoubtedly reduce the economic use of rain water, little can be done to control such waste.

8:3. TRANSPIRATION LOSSES OF WATER—MAGNITUDE

After water enters the plant, it may be utilized in the production of new compounds or may engage in cell activities without molecular change. By maintaining turgor and by facilitating quick shifts of nutrients and food

tion," Reprinted with revised bibliography, 1927, from *Appendix V of the Final Report of the National Waterways Commission*, 1912; and Wicht, C. L., "An Approach to the Study of Rainfall Interception by Forest Canopies," *Jour. S. African Forestry Assoc.*, 6: 54–70, 1941.

[2] Haynes, J. L., "Ground Rainfall under Vegetative Canopy of Crops," *Jour. Amer. Soc. Agron.*, 32: 176–184, 1940.

from one part of the plant to another, water makes possible the intricate metabolic processes that are known to take place.

Because of the readiness with which moisture passes through the stomata of plants into the atmosphere, large quantities must be taken from the soil if the plant is to maintain its proper turgor and function in a normal manner. This loss, called transpiration, is of such magnitude as often to make the maintenance of adequate moisture in the soil a difficult problem. In fact, the farmers' main concern during the growing season is likely to be that of insufficient moisture.

Transpiration ratio. As might be expected, the pounds of water transpired for every pound of above ground dry matter produced in the crop is very large. This figure, called the *transpiration ratio,*[3] ranges from 200 to 500 for crops in humid regions, and almost twice as much for those of arid climates. The following data (Table 8:2) drawn from various investigators give some idea of the water transpired by different crops.

Table 8:2. Transpiration Ratios of Plants as Determined by Different Investigators

Crop	*Harpenden, England*[4]	*Munich, Germany*[5]	*Dahme, Germany*[6]	*Madison, Wisconsin*[7]	*Pusa, India*[8]	*Akron, Colorado*[9]
Barley	258	774	310	464	468	534
Beans	209	...	282	...	...	736
Buckwheat	...	646	363	...	...	578
Clover	269	...	310	576	...	797
Maize	...	233	...	271	337	368
Millet	...	447	...	...	...	310
Oats	...	665	376	503	469	597
Peas	259	416	273	477	563	788
Potatoes	...	...	...	385	...	636
Rape	...	912	...	...	...	441
Rye	...	...	353	...	...	685
Wheat	247	...	338	...	544	513

[3] A brief discussion of the various methods used in determining the transpiration ratio will be found as follows:

Montgomery, E. G., "Methods of Determining the Water Requirements of Crops," *Proc. Amer. Soc. Agron.*, 3: 261–283, 1911.

Briggs, L. J., and H. L. Schantz, *The Water Requirements of Plants,* Bulletin 285, Bureau of Plant Industry, U. S. Dept. of Agriculture, 1913.

As these citations indicate, the term *water requirement* is often used instead of *transpiration ratio.* The latter term, however, seems to be the more desirable as it is yet to be shown that transpiration is absolutely necessary for the normal growth of plants. Apparently it is a lavish loss of water instead of an actual requirement.

[4] Lawes, J. B., "Experimental Investigation into the Amount of Water Given Off by Plants During Their Growth," *Jour. Hort. Soc.*, London, 5: 38–63, 1850.

[5] Wollny, E., *Der Einfluss der Pflanzendecke und Beschattung auf die Physikalischen*

Much of the variation observed in the ratios quoted arises from differences in climatic conditions.[10] As a rule, the less the rainfall, the lower is the humidity and the greater is the relative transpiration. This accounts for the high figures obtained in arid and semi-arid regions. In general, temperature, sunshine, and wind vary together in their effect on transpiration. That is, the more intense the sunshine, the higher is the temperature, the lower is the humidity, and the greater is likely to be the wind velocity. All this would tend to raise the transpiration ratio.

The factors inherent in the soil itself are of special interest as regards transpiration, since they can be controlled to a certain extent under field conditions. In general, an increase in the moisture content of a soil above optimum results in an increased transpiration ratio. This has been established by a number of investigators.[11]

Moreover, the amount of available nutrients and their balanced condition are also concerned in the economic utilization of water. The data available show that the more productive the soil, the lower is the transpiration ratio[12] provided the water supply is held at optimum. Therefore, a farmer in raising the productivity of his soil by drainage, lime, good tillage, farm manure, and fertilizers provides at the same time for a greater amount of plant production for every unit of water utilized. The total quantity of water taken from the soil, however, will probably be larger.

Eigenschaften und die Fruchtbarkeit des Bodens, Wiegandt, Hempel and Parey, Berlin, 1877, p. 125.

[6] Hellriegel, H., *Beiträge zur den Naturwissenschaftlichen Grundlage des Ackerbaus,* Friedrich Vieweg und Sohn, Brunswick, Germany, 1883, p. 663.

[7] King, F. H., *Physics of Agriculture,* published by author, Madison, Wis., 1910, p. 139.

[8] Leather, J. W., *Water Requirements of Crops in India,* Memoirs, Dept. Agr., India, Chem. Series, I, No. 8: 133–184, 1910, and No. 10: 205–281, 1911.

[9] Briggs, L. J., and H. L. Schantz, "Relative Water Requirements of Plants," *Jour. Agr. Res.,* 3: 1–63, 1914. Also, *The Water Requirements of Plants,* Bulletin 284, Bureau of Plant Industry, U. S. Dept. of Agriculture, 1913.

[10] Briggs, L. J., and H. L. Schantz, "Daily Transpiration During the Normal Growth Period and Its Correlation with the Weather," *Jour. Agr. Res.,* 7: 155–212, 1916.

Kiesselbach, T. A., *Transpiration as a Factor in Crop Production,* Research Bulletin 6, Nebr. Agr. Exp. Sta., 1916.

[11] Hellriegel, H., *Beiträge zur den Naturwissenschaftlichen Grundlage des Ackerbaus,* Friedrich Vieweg und Sohn, Brunswick, Germany, 1883, p. 628.

Montgomery, E. G., "Methods of Determining the Water Requirements of Crops," *Proc. Amer. Soc. Agron.,* 3: 276, 1911.

[12] Montgomery, E. G., *Water Requirements of Corn,* 25th Annual Report, Nebr. Agr. Exp. Sta., 1912, p. 11; and Singh, B. N., and B. K. Mehta, "Water Requirement of Wheat as Influenced by the Fertility of the Soil," *Jour. Amer. Soc. Agron.,* 30: 395–398, 1938.

Inches of water removed. Since it may be seen from the transpiration ratios quoted that the amount of water necessary to mature the average crop is very large, a concrete example under humid conditions may be cited to advantage. Let us assume that a representative crop of oats produces 4,000 pounds of dry matter an acre and has a transpiration ratio of 500. The amount of water withdrawn from the soil during the growing season would be equivalent to almost 9 inches of rain. The corresponding figure for corn, assuming the dry matter as 6,000 pounds and the transpiration ratio as 350, would be over 9 inches.

These figures do not include runoff, drainage, and evaporation from the soil surface, nor the interception of rain by the above-ground parts of plants. These losses for the year usually greatly exceed the removal by crops but for the growing season the latter generally exerts the major draft on the water actually in soils. The possibility of moisture being a critical, if not the most critical, factor in crop production, is thus obvious.

In spite of the magnitude of crop transpiration it must be more or less satisfied if adequate harvests are to be attained. Therefore, when moisture is critical, as it very often is, competing losses should be curtailed as much as possible. Reserving runoff and percolation losses for later consideration (pages 255 and 243), two other competing types of water removal loom large just before and especially during the growing season—(1) weed transpiration and (2) evaporation of water from the surface of the soil. Their magnitude and control will be considered in order.

8:4. WEED TRANSPIRATION AND WEED CONTROL

Weeds, especially if they are active during the early part of the season, usually retard the growth of crops, often to a serious extent. The detrimental influence is due to the absorption of nutrients that might otherwise be used by the crop and to competition for water. The magnitude of such rivalry is known to be great. This can be inferred with certainty from the transpiration data already cited for crop plants. The control of weeds is, therefore, to a certain extent a control of moisture, the attempt being to eliminate the transpiration of certain plants to the advantage of others.

While tillage usually tends to maintain the physical condition of the soil, the killing of weeds thereby is an important consideration also. In fact, cultivation often can be justified only for such a purpose. One of the advantages of a good rotation also relates to the discouragement of weeds. Cultivated crops alternating with small grains and meadow so change the conditions of growth and seeding as to aid in weed control. Plowing at

particular times, the growing of crops that exert a smothering effect, and the use of clean seed are specialized attempts to accomplish the same result. These are all old and well tested practices but they have by no means entirely solved the farm weed problem.

Newer weed control methods. Other and newer types of weed control are now being utilized in addition to those already mentioned. While flame machines have been tried, the use of certain selective herbicides is proving much more successful. The plant poisons commonly employed are water soluble and are sprayed on in very dilute concentrations since they are exceedingly potent. The idea is to kill the weeds but leave the crop plant practically unaffected.[13] Three different types of application are in use: (1) *pre-planting* treatment, the herbicide being sprayed on the soil before seeding but after seedbed preparation; (2) *pre-emergence* dosage, that is, after planting but before the sprouts appear above ground; and (3) *post-emergence,* the poison being applied to both the weeds and the crop. In general, the latter method is most effective and satisfactory although the other types of treatment have exceptional merit under certain conditions.

It must not be inferred from what has been said, that weeds are always detrimental. When developing late in the season, they may hasten the maturity of the crop by using available water and nutrients. Again, they may act as a green-manuring crop, increasing the organic residues that enter the soil when it is plowed. In orchards, weeds sometimes are used as a cover-crop and aid materially in protecting the soil and in increasing its humus supply. However, these are special cases. In general, weeds should be kept under reasonable control as they so quickly become an expensive nuisance.

8:5. EVAPORATION AT THE SOIL SURFACE—FACTORS AFFECTING

While the extent to which water vapor translocates within the soil is open to question (see page 209), the removal of water at the surface by vaporization undoubtedly is very large and of great practical concern. Several factors by their joint influence upon the vapor-pressure gradient

[13] The research on herbicides is progressing at such a rate as to quickly render out of date any publications that might now be cited. For an excellent discussion of the subject up to 1949, consult Crafts, A. S., and W. A. Harvey, "Weed Control," *Advances in Agronomy,* Vol. I: 289–315, A. G. Norman, Ed., Academic Press, Inc., New York, 1949. This article carries an excellent citation of literature.

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(see footnote, page 208) account for this wholesale loss of water by evaporation. The principal conditions are (1) the relative humidity of the atmosphere, (2) the temperature difference of the two moisture phases, (3) wind action, and (4) the amount of water at the soil surface and especially its rate of replacement by capillarity from below.

Relative humidity. Let us consider the moisture content of a soil and the temperature of both air and moist soil to be momentarily constant. Any changes in the vapor-pressure gradient and hence in the rate of evaporation will be determined by fluctuations in the relative humidity of the atmosphere immediately above. The lower the relative humidity the more pronounced will be the vaporization tendency. Sometimes the relative humidity of the atmosphere approaches 100 per cent. Under this condition evaporation might not only cease but condensation could be induced. Since relative humidity fluctuates rather widely from time to time, it cannot but exert a variable yet important influence upon the loss of water from soil by evaporation.

Temperature. Temperature differences, especially as occasioned by sunshine, play a particularly important part in influencing the vapor-pressure gradient at the surface of soils. In direct sunlight the soil and its water often have temperatures several degrees above that of the atmospheric air. This increases the vapor pressure and so markedly steepens the gradient that evaporation is greatly encouraged.

In fact this temperature effect on vaporization is usually much more important than that resulting from a lowering of the relative humidity of the air. For instance, raising the temperature of the water only 5° C. above that of the atmospheric air is equivalent in its effect on the vapor-pressure gradient to a lowering of the relative humidity about 35 per cent.[14] Hence, temperature difference is a major control of the vapor-pressure gradient and, therefore, of the surface evaporation of water from soils.

Wind. At the same time, if a dry wind is stirring, the accumulated water vapor is continually swept away, the moist air being replaced by that with a lower relative humidity. This tends to maintain the vapor-pressure gradient and evaporation is greatly encouraged. The drying effect of even a gentle wind is noticeable even though the air in motion may not be at a particularly low relative humidity. Hence, the capacity of a heavy wind operating under a steep vapor-pressure gradient to enhance evaporation

[14] Curtis, O. F., "Comparative Effects of Altering Leaf Temperatures and Air Humidities on Vapor-Pressure Gradients," *Plant Physiol.*, 11: 595–603, 1936.

both from soil and plants is tremendous. Farmers of the Great Plains dread the *hot winds* characteristic of that region.

Capillarity. Evaporation of water from soils takes place almost entirely at the immediate surface, exceptions being where large cracks occur which allow a thermal loss directly from the subsoil. Hence, unless the soil is kept moist at its surface, a vapor-pressure gradient adequate for rapid evaporation cannot be maintained any length of time. Rain may temporarily wet the surface but for evaporation to be of serious magnitude a phenomenon already discussed must be active; namely, capillarity. Were it not for this upward pumping action, the loss of water by vaporization would be of little practical significance.

In evaluating the effect of this upward movement of water in respect to evaporation, two things should be considered: (1) the type of water influenced and (2) the depth to which the soil may suffer moisture losses in this way. As to the former, it is already known that only the soil water held at the lower tensions can readily respond to capillarity. This is the moisture at an energy level in the neighborhood of .50 of an atmosphere. Since this moisture is easily available to plants, its loss by evaporation, even in regions of high rainfall, is likely to be serious.

In respect to the depth to which soils may be depleted by this evapo-capillary pumping, soil physicists are agreed that the distance is far short of the 4, 5, or even more feet sometimes postulated.[15] The conditions that impede and interrupt the flow are such as to allow it to deliver important amounts of water to the surface only through comparatively short distances. Some investigators think that the rate of evaporation is often so rapid as to cause the moisture column to break relatively near the surface, and that this is one of the major inhibitions. But whatever the explanation, a 20- or 24-inch depth is probably a maximum range. In most cases, however, perhaps only the water of the furrow-slice suffers appreciable diminution by surface evaporation,[16] especially if vigorously absorbing roots are

[15] See Cameron, F. K., *The Soil Solution*, The Chemical Publishing Company, Easton, Pa., 1911, p. 23.

McGee, W. J., *Field Records Relating to Subsoil Water*, Bulletin 93, Bureau of Soils, U. S. Dept. of Agriculture, 31–32, 1913.

[16] Leather, W. J., "The Loss of Water from Soil during Dry Weather," *Mem. Dept. Agr., Agr. Res. Inst.*, Pusa, India, Chem. Series I, 79–116, 1908.

Alway, F. J. and G. R. McDole, "Relation of the Water-Retaining Capacity of a Soil to Its Hygroscopic Coefficient," *Jour. Agr. Res.*, 9: 27–71, 1917.

Veihmeyer, F. J., "Some Factors Affecting the Irrigation Requirements of Deciduous Orchards," *Hilgardia* 2: 125–291, 1926–27.

Bouyoucos, G. J., "Capillary Rise of Moisture in Soil under Field Conditions as

present to intercept the upward moving water and break the capillary contacts.

8:6. MAGNITUDE OF SURFACE EVAPORATION

In spite of the fact that evaporation is subject to several variable controls and that only the upper and comparatively shallow layer of soil is seriously subject to such loss, the moisture removal in the aggregate is surprisingly large. This is because all of the water as it enters and infiltrates the soil must pass through this critical zone and of necessity must pay an *evaporation toll,* large or small, according to soil and climatic conditions.

Usually this toll is large. As an example, the evaporation from a bare soil in the Rothamsted (England) lysimeters[17] averaged 14.7 inches annually and showed little variation from year to year in spite of a considerable range in precipitation. The average rainfall for the period of the experimentation was 28.8 inches. On this basis about 50 per cent of the rain received was lost as thermal water. Even though cropping undoubtedly reduces this direct loss, evaporation will still be a factor of major importance. Naturally data from different localities vary with the climate, the soil under study, and the landcover and its management.

Let us generalize further assuming in this case that the land is cropped and is yielding satisfactory harvests under a system of general or dairy farming in a humid temperate region. It is often estimated that under these conditions runoff plus percolation will account roughly for 50 per cent of the annual rainfall received by the land. The remainder is, of course, divided between the vegetative cover and total evaporation, the latter including the vaporization from the soil surface plus that encouraged by crop interception of rain. It has been shown (page 223) that a good crop of corn or oats will require the equivalent of from 9 to 10 inches of rain. Assuming a precipitation of from 36 to 40 inches annually, this would indicate that from 9 to 10 inches are lost by total evaporation.

The general deduction is clear—evaporation from the surface of the soil is a vitally important factor in crop production. While the illustrative calculations would be somewhat different for arid and semi-arid regions and for the tropics, the final conclusion would, in general, be much the same.

Studied by the Electrical Resistance of Plaster Paris Blocks," *Soil Sci.,* 64: 71–81, 1947.

[17] Hall, A. D., *The Book of the Rothamsted Experiments,* E. P. Dutton and Company, Inc., New York, 1917, p. 2.

Nor is the evaporation problem absent from irrigated lands, especially when water is expensive and none too plentiful for the acreage to be served.

Surface evaporation affects water that might otherwise be used readily by the crop, and thus the competition is direct and often disastrously keen. Moreover, evaporation losses frequently are at their maximum at the time that crop demands are greatest. If weeds are critical in soil management, soil moisture evaporation because of its magnitude undoubtedly is also serious.

8:7. EVAPORATION CONTROL—MULCHES

Any material used at the surface of a soil primarily to prevent the loss of water by evaporation or to keep down weeds may be designated as a mulch. In some cases, foreign materials, that is substances not already on the land, are merely spread over the soil surface. Manure, straw, leaves, and other litter may be used successfully. Such mulches, while highly effective in checking evaporation and in preventing weed growth, are not generally applicable to most field crops, especially those that require intertillage. Their use is, therefore, limited to strawberries, blackberries, fruit trees, and such other crops as require infrequent cultivation, if any.

Paper mulch. A specially prepared *paper* has met with some favor as a mulch.[18] This paper is spread and fastened down either between the rows or over the rows, the plants in the latter case growing through suitable openings. This mulch can be used, however, only with crops planted in rows or in hills. As long as the ground is covered, evaporation and weeds are checked and, in some cases, remarkable crop increases have been reported. Unless the rainfall is torrential, the paper does not seriously interfere with the infiltration of the rain water.

The paper mulch has been employed with considerable success in the culture of pineapples in Hawaii where the idea originated and with other crops elsewhere. Whether this type of mulch will ever be used to any extent in trucking and vegetable gardening in the United States is doubtful. The

[18] Flint, L. H., *Crop-Plant Stimulation with Paper Mulch*, Technical Bulletin 75, U. S. Dept. of Agriculture, 1928.

Smith, Alfred, "Effect of Paper Mulches on Soil Temperatures, Soil Moisture, and Yields of Certain Crops," *Hilgardia*, 6: 159–201, 1931.

Robbins, P. W., "The Use of Paper Mulch in Forestry Nursery and Field Plantations," *Jour. Forestry*, 30: 315–418, 1932.

Hutchins, A. E., *Mulch Paper in Vegetable Production*, Bulletin 298, Minn. Agr. Exp. Sta., 1933.

cost of the paper and the difficulty of keeping it in place may be such as to offset entirely any increase in crop that may result.

Stubble mulch. A mulch somewhat different from those already described, especially as to mode of establishment, is the *stubble* or *trash mulch* used mostly in sub-humid and semi-arid regions. In this case the mulching materials have been grown in place and consist of the refuse of the previous crop. Oats stubble and straw, corn stalks, and like residues are good examples. By the use of suitable implements a seedbed can be prepared and the crop planted, leaving the organic trash on the surface to act as a mulch. (See Fig. 8:2.) In the case of row crops, modified tillage implements make cultivation possible without greatly disturbing the surface layer. Although the use of such a mulch has been found to conserve moisture in some cases, its main effectiveness seems to be that of controlling wind erosion.[19]

Soil mulch. All of the mulches previously discussed are more or less foreign to the soil, merely covering its surface, thereby obstructing evaporation and at the time preventing weed growth. The last type of mulch to be considered is the *natural* or *soil mulch*. With proper tillage and favorable weather, a loose, dry layer of soil two or three inches deep may be established on the surface by sacrificing much of the water it contains. This layer, the soil mulch, tends to obstruct the upward capillary adjustment of water from the moist soil below and should reduce evaporation losses to a considerable degree. This interruption in the upward capillary transfer of water by the soil mulch seems to be due (1) to its lack of close contact with the moist horizons underneath, (2) to an increase in its noncapillary pores and a reduction in those favoring capillarity, and (3) to the resistance to wetting that most dry soils exhibit. It is doubtful, however, whether the over-all influence of a soil mulch, as it must be handled in the humid region, will result in a conservation of moisture. This will be pointed out in the following section.

[19] A considerable literature is already available regarding the establishment, management, and effects of stubble mulches. Some of the articles are cited below:

Duley, F. L., and J. C. Russel, "New Methods of Rainfall and Soil Moisture Conservation," *Ann. Rpt. Nebraska Crop Growers Assoc.*, 31, 1939.

Duley, F. L., and J. C. Russel, "Effect of Stubble Mulching on Soil Erosion and Runoff," *Proc. Soil Sci. Soc. Amer.*, 7: 77–81, 1942.

McKay, H. C., and W. A. Moss, *Stubble Mulch Farming in Southern Idaho*, Bul. 256, Idaho Agr. Exp. Sta., 1944.

McKay, H. C., and G. O. Baker, "Effect of Crop Residues on Erosion Control and Grain Yields under Southern Idaho Dryland Conditions," *Proc. Soil Sci. Soc. Amer.*, 11: 553–556, 1946.

8:8. DOES CULTIVATION CONSERVE MOISTURE IN HUMID REGIONS?

For many years, cultivation has been advocated in humid regions for three reasons: (1) the maintenance of a more satisfactory physical condition of the surface soil, (2) the killing of weeds, and (3) the conservation of moisture. The validity of the first two is unquestioned, if the tillage is applied with judgment, but there is some doubt as to the third, especially when a crop is on the land.

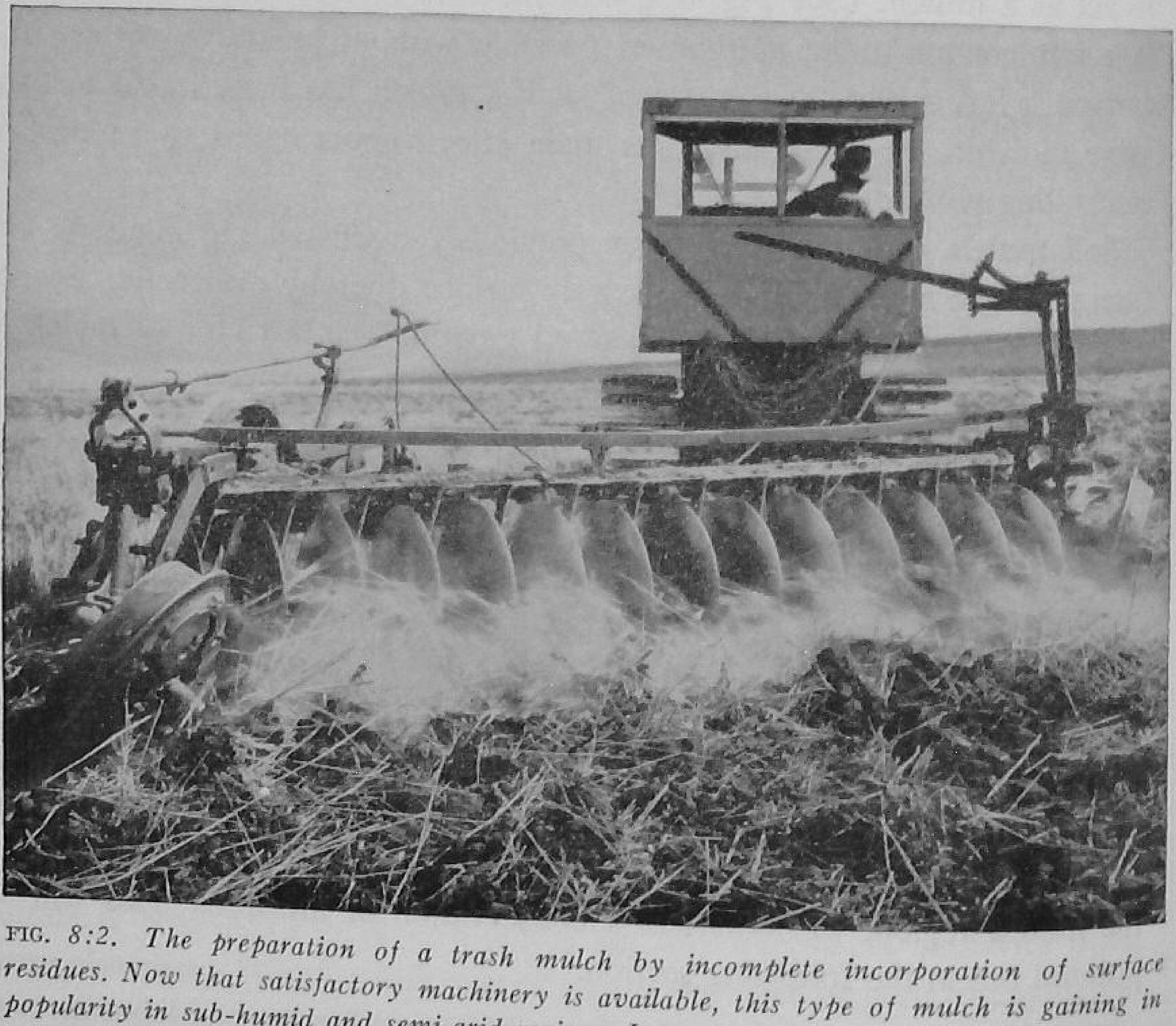

FIG. 8:2. *The preparation of a trash mulch by incomplete incorporation of surface residues. Now that satisfactory machinery is available, this type of mulch is gaining in popularity in sub-humid and semi-arid regions. It seems to have little effect on moisture control, but it protects the soil from wind erosion during fallow periods. (U. S. Soil Conservation Service photo.)*

Experimental results seem to indicate, particularly in humid regions, that no more moisture is available to a crop which is cultivated, and thereby mulched, than is available to a comparable crop unmulched. Of course, weeds must be under control and the physical condition of the soil satis-

factory in both cases. The ineffectiveness of the natural mulch seems to hold even during severe dry spells.

Moisture conservation *vs.* weed control. Such a conclusion is borne out by data from Illinois (Table 8:3) which indicate that, when weeds and physical conditions are controlled, the mulching effect of cultivation is of little benefit to the crop. In fact, the data hint that cultivation may at times be rather detrimental, possibly through root-pruning as well as waste of water. The main service of cultivation seemed to be the killing of weeds and the encouragement of a desirable tilth. These results are corroborated by a number of other investigations.[20]

Table 8:3. Effects of Various Methods of Tillage on the Yield of Corn and the Average Percentage of Moisture in the Soil to a Depth of 40 Inches. Average of Eight Years' Test at the University of Illinois. Mean Rainfall, 33.7 Inches[21]

Treatment	*Yield of Corn, Bushels per Acre*	*Average Percentage of Moisture in Soil*
Plowed and seedbed well prepared:		
1. Kept bare of weeds only	45.9	22.3
2. Weeds allowed to grow	7.3	21.8
3. Three shallow cultivations	39.2	21.9
Seedbed poorly prepared:		
4. Kept bare of weeds only	31.4	23.1

The failure of cultivation to be of benefit is by no means limited to field crops. Thompson,[22] after six years of experimentation with vegetables on a New York sandy soil, reported that cultivation and mulch formation gave no increase in the yield of carrots, cabbage, and tomatoes over uncultivated plots also kept free of weeds. The influence of mulching on beets and onions

[20] Cates, J. S., and H. R. Cox, *The Weed Factor in the Cultivation of Corn*, Bulletin 257, Bureau of Plant Industry, U. S. Dept. of Agriculture, 1912.

Call, L. E., and M. C. Sewell, "The Soil Mulch," *Jour. Amer. Soc. Agron.*, 9: 49–61, 1917.

Merrill, E. D., *Irrigation Investigation and Practice*, Report, 1923–1924, Univ. Calif. Agr. Exp. Sta., 46–47, 1924.

Veihmeyer, F. J., "Some Factors Affecting the Irrigation Requirements of Deciduous Orchards," *Hilgardia*, 2: 125–284, 1927.

Handbook of Experiments in Agronomy, Special Circular 53, Ohio Agr. Exp. Sta., 36–37, 1938.

[21] Mosier, J. G., and A. F. Gustafson, *Soil Moisture and Tillage for Corn*, Bulletin 181, Ill. Agr. Exp. Sta., 1915.

[22] Thompson, H. C., *Experimental Studies of Cultivation of Certain Vegetable Crops*, Memoir 107, Cornell Univ. Agr. Exp. Sta., 1927.

was very slight, probably within the experimental error. Beet yields were increased only 4 per cent by the maintenance of a soil mulch and 550 per cent by an adequate reduction of weed competition. The yield of only one vegetable crop, celery, was definitely increased by cultivation. The benefit here may have been due to the influence on the physical condition of the soil and not to the conservation of water.

Why soil mulches do not conserve moisture. Three reasons are commonly advanced for the ineffectiveness of cultivation in moisture control. In the *first* place, a large amount of moisture always escapes by evaporation long before the soil is dry enough for cultivation. Hence, the establishment of a soil mulch at this late date, even if it should be highly effective, cannot greatly influence the over-all loss of water by surface evaporation. *Secondly*, in many cases, this precultivation loss has already established a protective surface layer of air dry soil, which, although thin, may successfully cope with evaporation by obstructing capillarity. At this stage, therefore, the soil, except in certain cases, may need no further protection against surface evaporation.

Thirdly, the crop itself, if its root spread is wide and comparatively dense, may intercept upward moving moisture that might otherwise reach the soil surface; thus making a mulch still more unnecessary. Therefore, it would seem that the uncultivated and unmulched crop should have at least as much water at its disposal, providing weeds are not present, as the cultivated crop and perhaps on occasion considerably more.

The mere fact that a soil mulch usually fails to conserve water in a humid region, even if the drought period is long, does not mean that cultivation is unnecessary or undesirable. The Illinois experiments show it to be vitally necessary in the preparation and maintenance of a well aerated seedbed and in the control of weeds. But once these phases are taken care of, it is questionable, especially in a humid area, whether enough benefit is derived from a soil mulch as to make cultivation worth while. In fact, the waste of water and root-pruning may render overcultivation decidedly objectionable and extremely expensive. (See Fig. 8:3.)

8:9. VAPORIZATION CONTROL IN HUMID REGIONS

From what has been said it seems that little in general can be done in humid regions in respect to the control of the vaporization removal of water from farm lands. Losses due to crop transpiration and interception are conceded as beyond control. The more vigorous the growth of the crops,

the larger will be these two removals, especially transpiration. The ineffectiveness of a soil mulch and the waste of water incidental to its establishment have been cited. Although stubble and trash mulches are effective as well as feasible, they have not met with any great favor in humid regions. Artificial mulches, although satisfactory in gardens, nurseries, and orchards, are more or less out of the question with field crops.

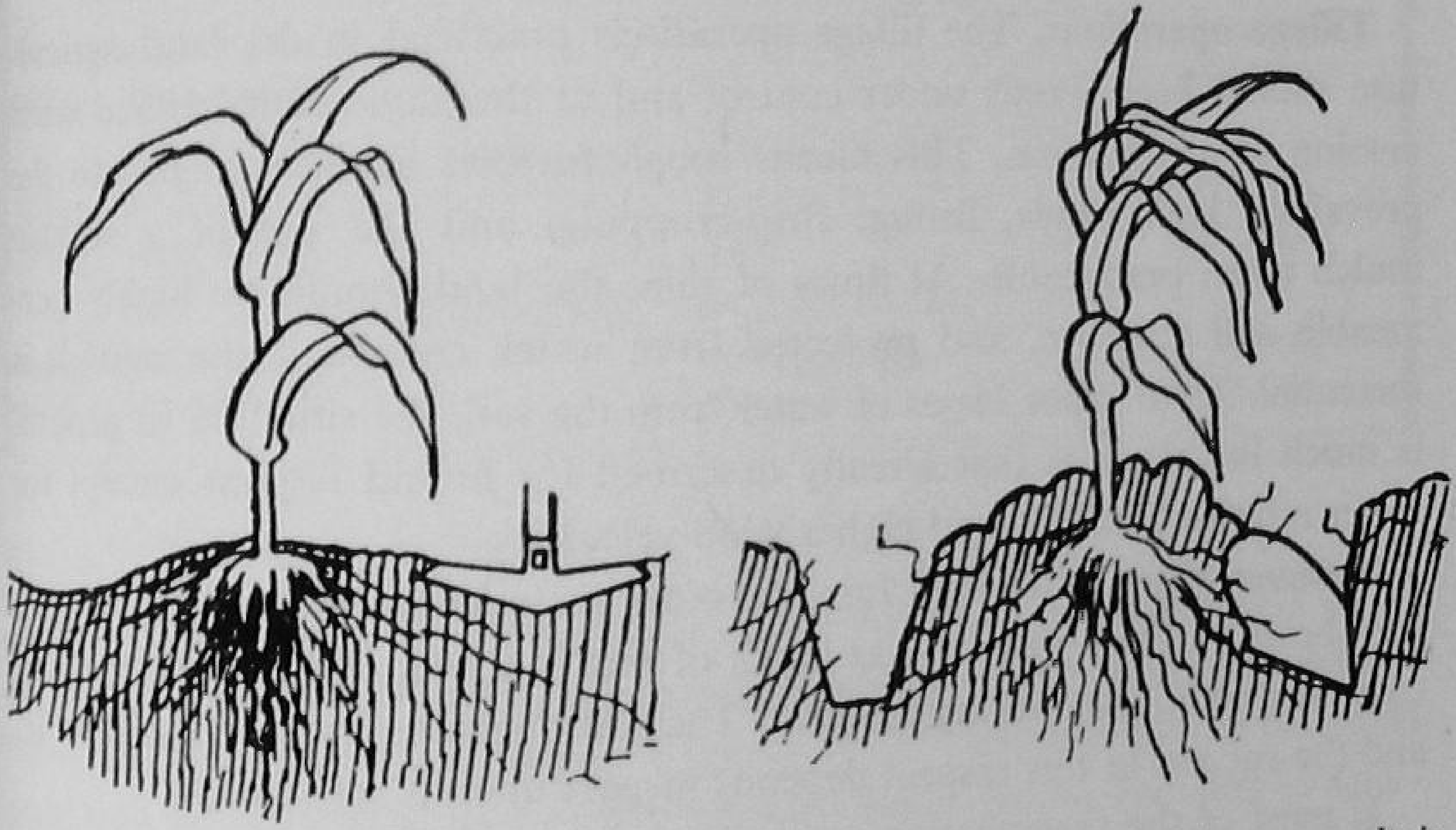

FIG. 8:3. *The deep cultivation of intertilled crops such as corn (right) may result in serious root pruning. Hence cultivation for the killing of weeds should be shallow (left) even early in the season. If weeds are under control and the structure of the soil is satisfactory, further intertillage usually is unnecessary. (From Donald, L., "Don't Blame the Weather,"* Comm. Fert. *pp. 19–24, Feb. 1946.)*

This leaves the control of weeds as about the only effective and practicable means in humid regions of influencing vaporization. Their elimination, however, usually does not result in a reduction of soil moisture loss *in toto* but merely insures a greater amount of water available for crop transpiration. This, of course, is very desirable and usually is the ultimate objective in the moisture management of field soils. The attention now being given to improved methods of weed control is well placed.

8:10. VAPORIZATION CONTROL IN SEMI-ARID AND SUB-HUMID REGIONS

When the average annual rainfall of a region is very much below 25 inches, it would seem that crop production would be impossible without irrigation. Yet between the limits of 15 to 20 inches, certain crop plants may

be grown successfully, especially when much of the rainfall comes in the spring and early summer. The system adopted is often called *dry-land farming.* It consists essentially (1) in using special varieties of such crops as wheat, corn, sorghums, rye, and the like, (2) in reducing the rate of seeding to correspond to the limited amounts of moisture that probably will be available, and (3) in employing tillage practices that conserve and economize water. It is only the latter phase that need concern us here.

Tillage operations. The tillage operations practiced in dry-land agriculture should keep weeds under control and at the same time reduce wind erosion to a minimum. This means rough furrows at right angles to the prevailing high winds, listing, strip-cropping, and the use of a stubble mulch when practicable. At times of rain, the land should be highly permeable and retentive, and protected from water erosion if the rainfall is torrential. As to vapor losses of water from the soil, the situation in general is much the same as that already described for humid regions except for lower relative humidity and higher wind velocities.

Summer fallow. Dry-land farming often includes a *summer fallow,* the idea being to catch and hold as much of one season's rain as possible and carry it over for use during the next. The soil profile is used as a reservoir, and the success in this respect depends in part upon a soil mulch.

If most of the precipitation comes in the spring and early summer, it is practicable to establish the soil mulch near the beginning of the dry season and trap more or less effectively the water present. As cultivation during the summer and fall is necessary only to control weeds, the sacrifice from stirring the soil is largely that occurring when the mulch is first established, since it is seldom wetted during the dry period. Under such a climatic condition, further loss of water is not great. Possibly one-half or even more of the season's precipitation may be carried over to the next year. Then, if that season is not too dry, a satisfactory crop will be grown, the current rainfall being supplemented by the carry-over. (See data in Table 8:4.)

Here, then, is a situation where an appreciable amount of moisture may be conserved by the proper handling of the land. But it is a case specific for dry-land areas and should not be confused with the situation in humid regions. In the latter, summer fallowing is detrimental and unnecessary. Moreover, the creation of a soil mulch by cultivation occurs when intertilled crops occupy the lands. This is quite a different setup, climatically as well as otherwise, from the simple summer fallowing practiced in dry-

land agriculture, where there is no crop on the land and the mulch remains dry over a considerable period of time.

Table 8:4. **The Influence of Summer Fallow in Alternate Years on the Available Moisture at Wheat Seeding Time and the Yield of Wheat Following**[23]

Treatment	*Available Water at Seeding Time*	*Wheat Yields*
	MANDON, N. D. (AVE. 20 YEARS)	
Wheat after fallow	7.08 inches	4120 lbs.[24]
Wheat after wheat	2.48 "	2300 lbs.
	HAYS, KAN. (AVE. 23 YEARS)	
Wheat after fallow	7.96 inches	27.3 Bu.
Wheat after wheat	2.90 "	17.4 Bu.
	GARDEN CITY, KAN. (AVE. 13 YRS.)	
Wheat after fallow	4.67 inches	15.5 Bu.
Wheat after wheat	1.08 "	8.2 Bu.

8:11. EVAPORATION CONTROL ON IRRIGATED LANDS

In areas of low rainfall or when precipitation is so distributed as to be insufficient for crops at critical times, *irrigation,* the artificial application of water to land, is common. (See Fig. 8:4.) While irrigation has been practiced for centuries, it is only in recent years that its use, due to engineering facilities, has been extended to great areas the world over. Now, thousands of acres of arid or semi-arid lands, that otherwise would be barren, are producing abundant crops of many kinds. In the United States, most of the irrigated land lies west of the 100th meridian and embraces perhaps 21 million acres. Moreover, irrigation in the more humid areas to the eastward is decidedly on the increase.

Control principles. It is hardly necessary to emphasize that the principles already discussed relating to the movement and distribution of moisture through the soil, its losses, and its plant relationships, apply just as rigidly for irrigation water as for that reaching the soil in natural ways. Although the problems inherent to liquid water such as runoff and erosion, infiltration, percolation, and drainage are subject to better control under irrigation, they are met and solved in much the same way as for humid region soils. The

[23] North Dakota data from Thysell, J. C., *Conservation and Use of Soil Moisture at Mandan, North Dakota,* U. S. Dept. of Agriculture, Tech. Bul. 617, 1938. Kansas Data from Throckmorton, R. I., and H. E. Meyers, *Summer Fallow in Kansas,* Kans. Agr. Exp. Sta., Bul. 293, 1941.

[24] Total plant yields.

situation regarding vapor losses, however, is much more critical, indeed more so at times than even with contiguous soils under dry-land cropping. Let us briefly examine the situation.

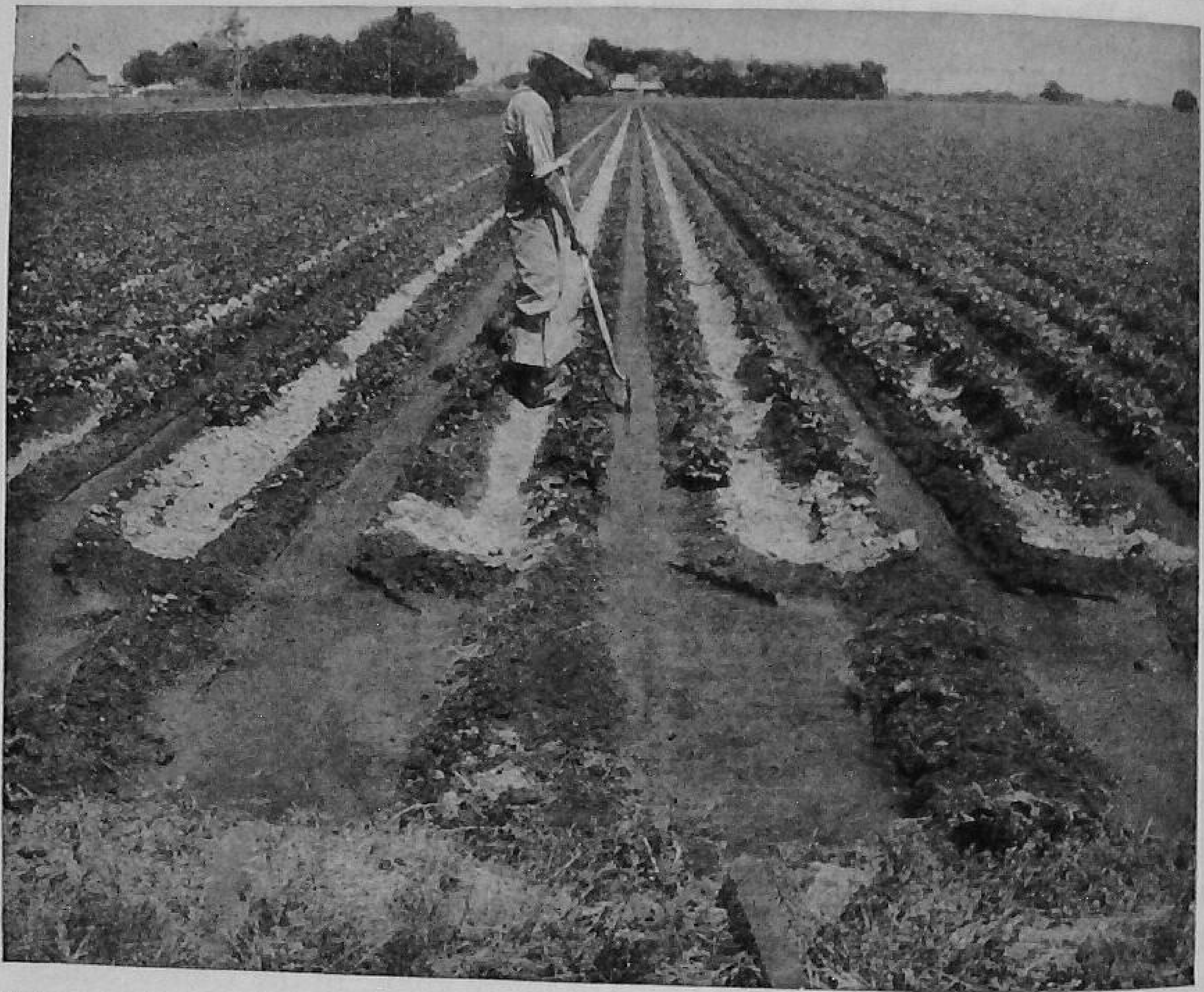

FIG. 8:4. *A typical irrigation scene. The use of easily installed siphons (foreground) reduces the labor of irrigation and not only speeds up the rate of application of the water but also makes it easier to control. Note the upward capillary movement of water along the sides of the rows. (Photo from Bureau of Reclamation, U. S. Dept. of Interior.)*

It is, of course, realized that in dry regions, with their low humidity, high wind velocities, and intense sunshine, vaporization of moisture is at a maximum. Consequently, the evaporation loss of water from moist soils is very rapid and competition with crops often extremely serious. Moreover, the gravity of the situation is greatly enhanced by high transpiration ratios which often are double those of crops grown under humid conditions. Therefore, methods of moisture conservation, especially after irrigation water has been added, are as important as with dry-land farming. Not only must economy be used in the application of water but also in respect to its utilization once it is in the soil.

Tillage methods both before and after irrigation thus become extremely important. A soil mulch undoubtedly is of considerable value, especially if the intervals between irrigations are long and the weather hot and dry. Here the situation is somewhat analogous to that of dry-land farming where the soil is used as a reservoir for water and the mulch once established will remain effective for a considerable period without further stirring.

Salt accumulation. A phenomenon closely correlated with evaporation and often met with on arid region lands under irrigation is that of the concentration of soluble salts at or near the soil surface. It seems that soils developed under low rainfall, and hence with practically no percolation loss of water, usually contain considerable amounts of salts, many of which are soluble. So long as these salts, largely the carbonates, bicarbonates, sulfates, and chlorides of calcium, magnesium, potassium, and sodium, are more or less uniformly disturbed through the profile, no great detrimental effect is exerted upon plants. This apparently is the situation in many of the soils cropped under the methods of dry land agriculture.

But, when such soils are irrigated and a plentiful supply of water is present in the upper part of the profile, the situation is radically changed. Evaporation occurs copiously at the soil surface. This in turn sets up capillarity, and moisture moves slowly upward carrying its burden of soluble salts. Even though film adjustment may be effective to a depth of only 15 or 20 inches, eventually it cannot fail but effect a considerable concentration of salts at or near the surface. (See Figs. 8:5 and 14:6.)

While this does not happen in all cases, it is of frequent occurrence on poorly drained soils. Hence, certain surface soils that originally were mildly alkaline become loaded with salts, giving rise to the *saline* or even *alkali* soils. (See page 414.) Such a development should by all means be prevented. The avoidance of over-irrigation and the holding of evaporation at a minimum apparently are the most effective means of attaining such an objective.

Due to ignorance and neglect thousands of acres of fertile arid region soils have been practically ruined. Although physical and chemical means of eradication are practiced (page 418), the solution lies fundamentally in careful irrigation and a reduction of any surface evaporation that tends to cause an upward movement of salts. Irrigation practice thus not only should apply the usual moisture regulations as intensively as under dry-land agriculture, but also must deal with a corollary moisture feature, salt

accumulation which is a manifestation of evaporation supported by capillarity.

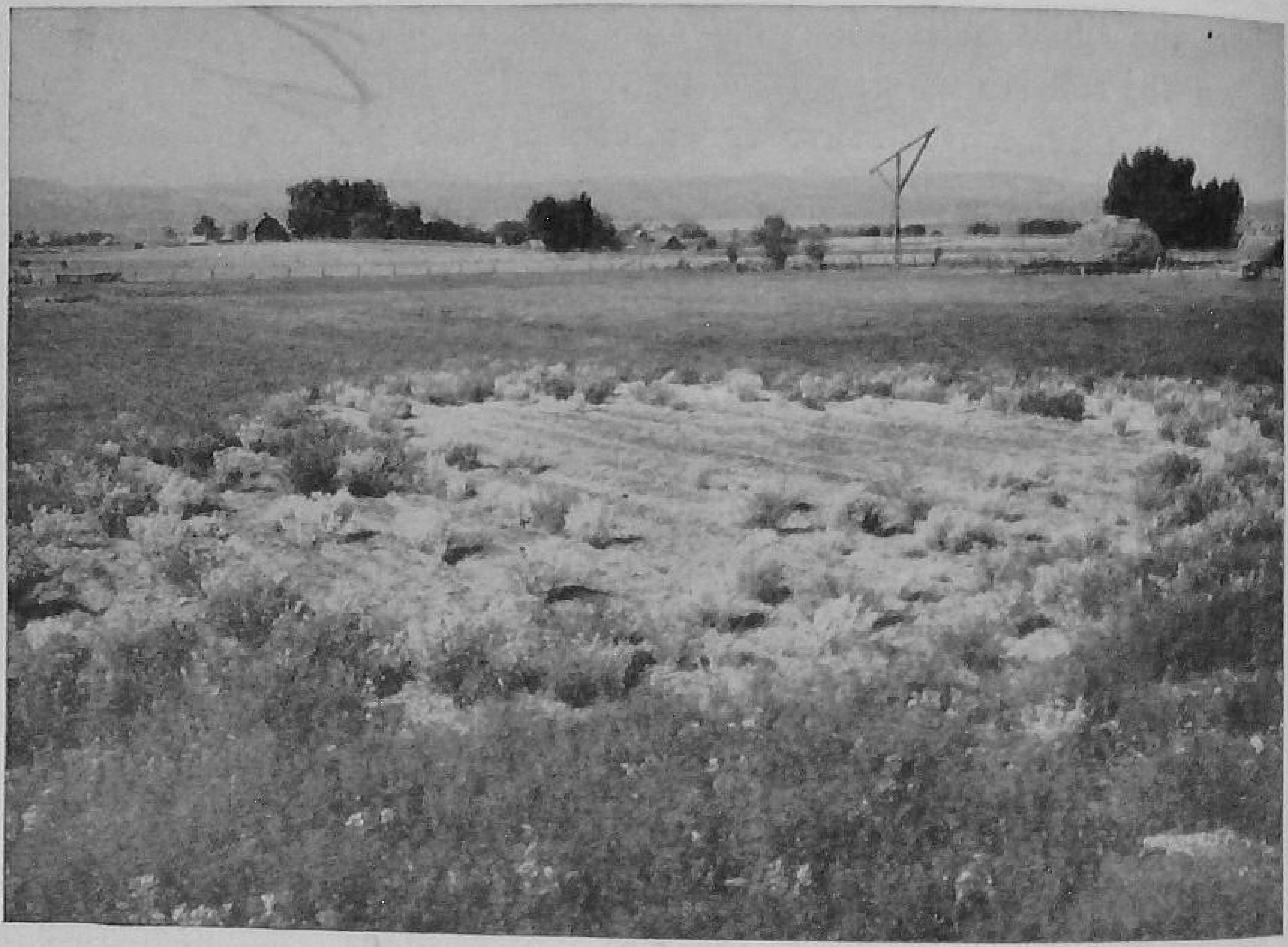

FIG. 8:5. *A white "alkali" spot in a field of alfalfa under irrigation. Because of upward capillarity and evaporation, salts have been brought to the surface where they have accumulated in amounts toxic to plants. (U. S. Soil Conservation Service photo.)*

CHAPTER

9 Liquid Losses of Soil Water and Their Control

IT HAS already been shown that vaporization losses from land surfaces are of vital practical concern but that they are not subject, except in certain cases, to any particularly drastic control.

The situation in respect to liquid losses, however, is radically different. (See Fig. 8:1.) *Firstly,* liquid losses may be modified and manipulated both as to rate of water removal and as to amount. *Secondly,* these losses involve water that in large degree is superfluous. Hence, the competition with crops usually is not serious as may be the case with evaporation and weed transpiration. And *thirdly,* the removal of this excess water results in leaching and sometimes in erosion, both of which at times may be serious. Vaporization, in contrast, entails a loss of water only.

Two types of liquid losses of water from soils are recognized (Fig. 8:1): (1) The downward movement of gravitational water (percolation) which frees the surface soil and upper subsoil of superfluous moisture (see Fig. 7:5), and (2) the runoff of excess water over the soil surface. Percolation, as noted above, usually results in the loss of soluble salts (leaching) and thereby may seriously deplete soils of certain nutrients. Runoff losses often include not only water, the infiltration of which is often desirable, but also may carry away appreciable amounts of soil (erosion). These two liquid losses of soil water with their concomitant effects will be considered in the order of their introduction above.

9:1. PERCOLATION AND LEACHING—METHODS OF STUDY

Two general methods of procedure are available for the study of percolation and leaching losses—the use of an effective system of *tile drains*

specially installed for the purpose, and the employment of *lysimeters.* For the first method an area should be chosen where the tile drain receives only the water from the land under study and where the drainage is efficient. A record of the amounts of flow throughout a term of years and analyses of the drainage water will throw light on the ordinary losses of water and plant nutrients from a normal soil under a known cropping system. The advantage of such a method of attack is that a large area of soil may be utilized under normal field conditions.

The lysimeter [1] method, however, has been the usual mode of approaching such problems. This method involves the determination of percolation and nutrient losses under somewhat more controlled conditions. The advantages over a tile drain system are that the variations in a large field are avoided, the work of conducting the study is not as great and the experiment is more easily controlled.

Types of lysimeters. Three major types of lysimeters have been used to study percolation: (1) the *block* or *monolith* type, (2) the *tank* type, and (3) the *Russian* type. In the *block* or *monolith* type of lysimeter a small column of soil is entirely isolated by appropriate means from the land surrounding it and its drainage water measured and analyzed. (See Fig. 9:1.) Sets of these lysimeters have been used in Europe as well as in this country.

The advantage of such a method of construction lies in the fact that the structural condition of the soil is undisturbed. However, the possibility of the water passing down between the soil column and the walls of the drain gauge may be urged as a disadvantage. Also, the blocks of soil being compared, although close together, may have been initially somewhat different, especially physically. Because of the extreme variability that characterizes some soils, this might be marked and would, of course, vitiate comparisons.

A second type of lysimeter, the *tank* type was used for much of the early work in the United States. The soil to be studied by this method is removed from the field and packed into tanks or some other suitable containers. Free drainage is allowed through the tanks and arrangements are made to collect the leachate. An example of the tank lysimeters are those used at Cornell University shown diagrammatically in Figure 9:2.

The advantages of this type of lysimeter is that several different soils

[1] From *lysi* meaning loosening and *meter,* to measure.

and cropping systems can be compared at one location. Also the variability of results obtained are somewhat less than under field conditions.

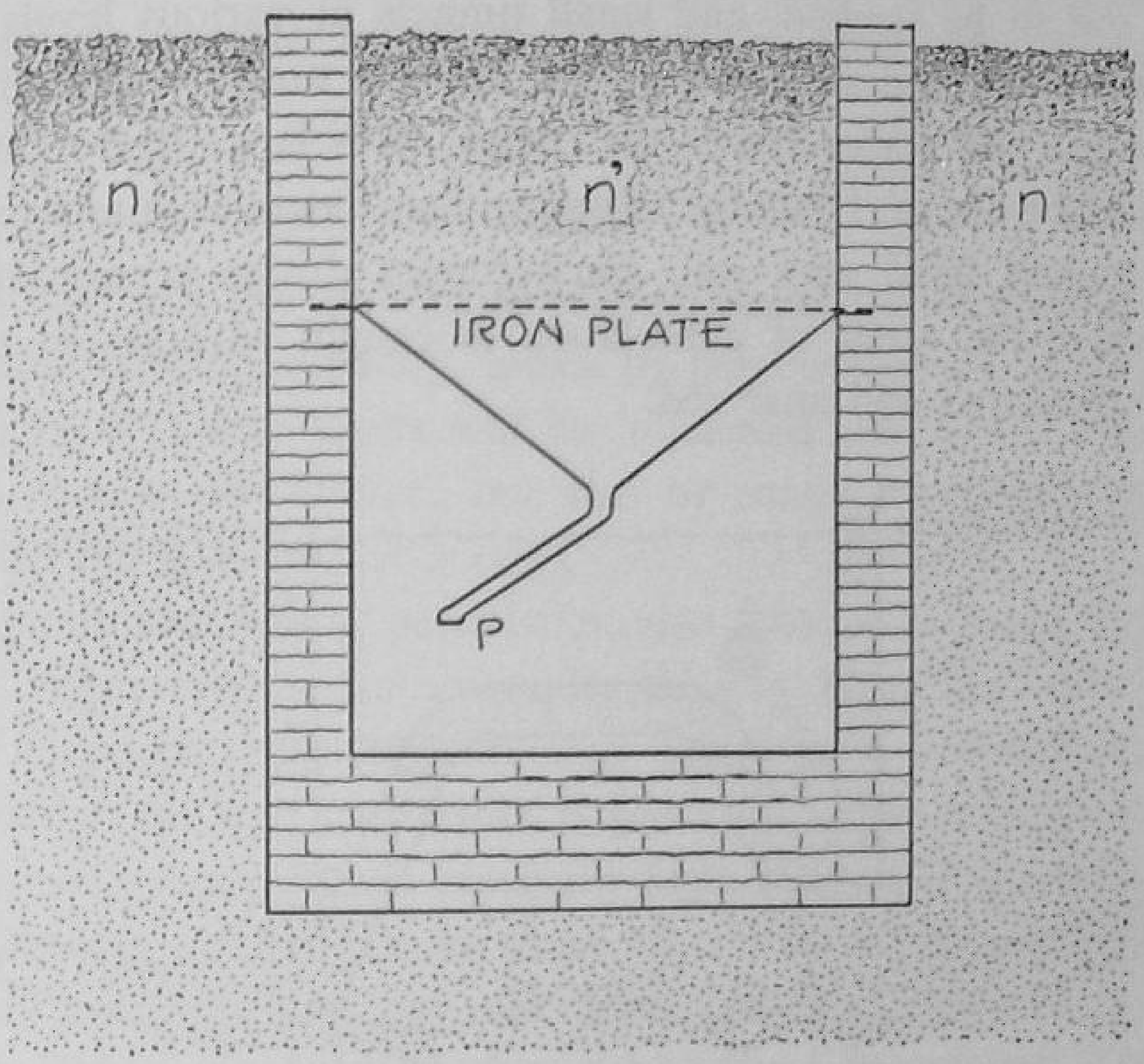

FIG. 9:1. *Cross section of monolith type of lysimeter at the Rothamsted Experiment Station, England. (N') soil block under study; (P) outlet for drainage water.*

There are two main disadvantages to the tank lysimeters, both of which are very serious. Firstly, the soil has been very much disturbed and it presumably never assumes its original physical condition. Secondly, runoff usually has not been allowed in this method. Consequently, a greater proportion of the precipitation received passes into the soil than would otherwise be the case. Percolation and nutrient loss data by this method thus often are higher than those obtained by other methods. In spite of these limitations, however, figures obtained with tank lysimeters are of great value in a comparative way.[2]

[2] See Mooers, C. A., and W. H. MacIntire, *Two Equipments for Investigation of Soil Leaching: I. A Pit Equipment. II. A Hillside Equipment*, Bulletin 111, Tenn. Agr. Exp. Sta., 1915.

MacIntire, W. H., and C. A. Mooers, "A Pitless Lysimeter Equipment," *Soil Sci.*, 11: 207–209, 1921.

Collison, R. C., and J. E. Mensching, *Lysimeter Investigations: I. Nitrogen and Water Relations of Crops in Legume and Non-Legume Rotations*, Technical Bulletin 166, N. Y. State Agr. Exp. Sta., 1930.

Morgan, M. F., *Soil Changes Resulting from Nitrogenous Fertilizers*, Bulletin 384, Conn. Agr. Exp. Sta., 1936.

For a criticism of the Cornell, Tennessee, and Geneva type of Lysimeters, see

A lysimeter of an entirely different type has been perfected in Europe, called in this country the *Russian lysimeter.*[3] A trench is dug beside the block of soil to be studied, and small tunnels at various levels are excavated horizontally under the soil profile. In each tunnel is placed a shallow funnel-shaped pan perforated at the center. This is wedged tightly against the soil horizon above. Drainage tubes are then installed, one for each pan, and the tunnels filled with soil. Each funnel drains separately into the trench, where the water of percolation is caught in suitable receptacles and later measured and analyzed.

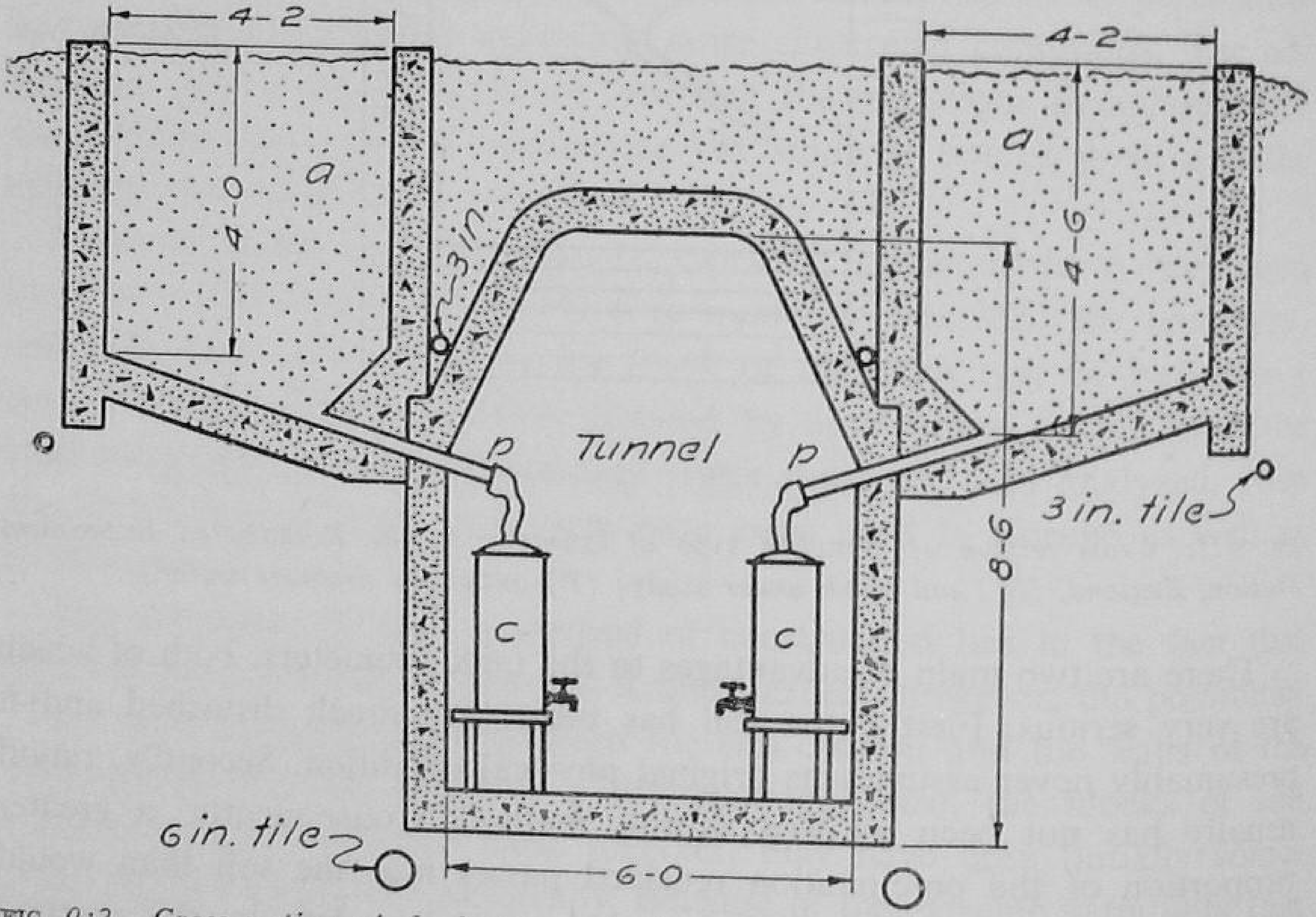

FIG. 9:2. *Cross-section of the lysimeter tanks at Cornell University, Ithaca, New York. Each tank is one of a series, one tunnel serving two rows. Soils under investigation (a), outlet (b), and can for catching drainage water (c). Surface runoff was not allowed.*

Such a lysimeter deals with undisturbed soil and thus avoids the objectionable feature of the tank type. Data [4] obtained by this method, however, show a considerable amount of variation and are at times con-

Joffe, J. S., "Lysimeter Studies: I. Moisture Percolation through the Soil Profile," *Soil Sci.,* 34: 123–142, 1932.

[3] Joffe, J. S., "A New Type of Lysimeter at the New Jersey Agricultural Experiment Station," *Science,* 70: 147–148, 1929.

[4] Joffe, J. S., "Lysimeter Studies: I. Moisture Percolation through the Soil Profile," *Soil Sci.,* 34: 123–142, 1932.

Collison, R. C., *Lysimeter Investigations: IV. Water Movement, Soil Temperatures,*

tradictory. Apparently these discrepancies are due to variations in the profile and to possible lateral movement of the water of percolation through wormholes, root passages, and cracks. This type of lysimeter can be expected to operate satisfactorily only in soils with fairly vertical drainage channels.

9:2. PERCOLATION LOSSES OF WATER

When at any time the amount of rainfall entering a soil becomes greater than its water-holding capacity, losses by percolation will occur if opportunity is offered. These losses will be influenced not only by the amount of rainfall and its distribution, but also by evaporation, the character of the soil, and the presence of a crop.

As the rainfall increases, percolation also tends to increase, being much greater in Pennsylvania, for example, than in Kansas. Evaporation has a marked influence, reducing drainage losses to a considerable degree. The percolation through sandy soils is generally larger than through clayey soils. Yet when evaporation is especially high, sandy soils have been known to percolate less annually than those of a heavier nature. Field crops, in that they not only intercept rain water but also absorb large amounts of moisture, have always been found to reduce percolation losses often very drastically.

Loss from bare soils. The results from the Rothamsted (England) lysimeters from 1871–1912 on a bare clay loam 5 feet deep are interesting in a comparative way (Table 9:1). The actual percolation is probably somewhat higher than under field conditions because of reduced runoff incident to experimental control.

Under the above conditions about 50 per cent of the rainfall was lost by percolation through this bare soil. The drainage loss was much lower in summer than in winter, the ratio being about 1 to 3. This was, no doubt, due to the high evaporation during the warmer season, as the rainfall was as great for the June–August period as for the December–February interval. Such a discrepancy serves again to emphasize the great loss of water from bare soil by vaporization.

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and Root Activity under Apple Trees, Technical Bulletin 237, N. Y. State Agr. Exp. Sta., 1935.

Lunt, Herbert A., *Forest Lysimeter Studies under Hardwoods,* Bulletin 449, Conn. Agr. Exp. Sta., 1941.

Kardos, L. T., "Lysimeter Studies with Cultivated and Virgin Soils under Subhumid Rainfall Conditions," *Soil Sci.,* 65: 367–381, 1948.

Table 9:1. Percolation Through a 60-inch Column of Bare Clay Loam. Rothamsted Experiment Station, Annual Average of Forty-two Years [5]

Periods	*Rainfall, Inches*	*Drainage, Inches*	*Percentage of Rainfall as Drainage*
Dec.–Feb.	6.77	5.58	82.4
Mar.–May	5.96	2.11	35.4
June–Aug.	7.83	1.82	23.2
Sept.–Nov.	8.29	4.50	54.2
Mean Total	28.85	14.01	48.5

These figures compare fairly well with Wollny's [6] summary on eighteen soils in Europe, studied under similar conditions. These soils, most of which were bare, showed a percolation loss of over 41 per cent of the precipitation. It must be remembered, however, that such data also are probably somewhat high, compared to bare field soils, because little run-off occurred.

That the figures cited above do not hold for soils of low rainfall is, of course, to be expected. Nor can they be applied specifically to other humid region soils. This latter statement is clearly substantiated by data from Illinois obtained with an erosion type of monolith lysimeter by Stauffer.[7] (See Fig. 9:3.) The slope was 1.4 per cent, the average annual precipitation 37.5 inches and the duration of the study about 6.5 years. Of the six bare silt loam blocks used, one (Muscatine) allowed ready drainage while another (Cowden) permitted only slow percolation. As a result 22.7 per cent of the annual precipitation drained through the first soil but only 3.6 per cent was lost from the latter in this manner. Obviously, soils vary tremendously as to percolation losses.

Percolation through cropped soils. It is interesting to consider now a situation where plants were growing on the soil. At Cornell University, Ithaca, New York, a study was made of two soils, bare and cropped, held in tank type lysimeters. The crops were corn, oats, wheat, and hay grown in rotation. The data (Table 9:2) for the Dunkirk and Volusia soils are for ten and fifteen years respectively.

[5] Hall, A. D., *The Book of the Rothamsted Experiments*, E. P. Dutton and Company, Inc., New York, 1917, p. 22.

[6] Wollny, E., "Untersuchungen über die Sickerwassermengen in verschiedenerarten," *Forsch, a. d. Gebiete d. Agri.-Physik.*, 2: 1–68, 1888.

[7] Stauffer, R. S., "Runoff, Percolate and Leaching Losses from Some Illinois Soils," *Jour. Amer. Soc. Agron.*, 34: 830–835, 1942.

Table 9:2. Average Annual Loss of Water by Percolation from Bare and Cropped Soils. Cornell Lysimeter Tanks [8] (No Runoff Allowed)

Conditions	*Rainfall, Inches*	*Percolation, Inches*
Dunkirk silty clay loam:		
Bare	32.41	24.92
Cropped	32.41	18.70
Volusia silt loam:		
Bare	33.22	20.90
Cropped	33.22	19.10

FIG. 9:3. *View of a set of monolith lysimeters at the University of Illinois. The pit between the two rows of lysimeters contains the vessels which catch the drainage water from the respective soil columns. Surface runoff is allowed and the amounts of soil and water lost in this manner are determined. (Courtesy of University of Illinois.)*

As might be expected, the presence of ordinary field crops definitely reduced the amount of drainage. If runoff had been allowed and less water had entered the soil, the influence of crops upon drainage loss would have

[8] Lyon, T. L., J. A. Bizzell, B. D. Wilson, and E. W. Leland, *Lysimeter Experiments, III*, Memoir 134, Cornell Univ. Agr. Exp. Sta., 1930.
Lyon, T. L., and J. A. Bizzell, *Lysimeter Experiments, IV*, Memoir 194, Cornell Univ. Agr. Exp. Sta., 1936.

been more marked. In fact, some cropped soils with annual rainfalls in excess of 30 inches show practically no percolation.[9] This occurs because of crops and evaporation draught and especially because runoff is high, accounting for perhaps 30 or 40 per cent of the annual precipitation. The type of rainfall, whether gentle or torrential, will be an important factor in respect to the amount of water entering the soil and hence upon the magnitude of percolation loss.

9:3. LEACHING LOSSES OF NUTRIENTS

Due to variable weather conditions, to inherent physical differences in soils, and to diversity in their management, particularly as to fertilization and cropping, it is practically impossible to forecast what the magnitude of the leaching losses of nutrients from any one soil is likely to be. Reference to almost any lysimeter data will substantiate this conclusion. Data thus obtained must, therefore, be used with caution and by no means subjected to unwarranted interpretation and application.

From the great mass of lysimeter data[10] available condensed figures (Tables 9:3 and 9:4) will first be quoted from several experiment stations. The diversity of the results cited lend weight to the caution voiced above.

The data from the various experiments are in fair agreement with respect to nitrogen and phosphoric acid losses. The leaching of calcium, potassium, magnesium, and sulfur, however, was much higher from the Cornell lysimeters. Undoubtedly, this was due largely to the fact that no runoff was allowed from these tanks since the rainfall was about the same at the other locations under consideration. That the soils used in the Cornell investigation had been greatly disturbed in filling the tanks also may have been a vitiating factor.

[9] Kilmer, V. J., *et al*, "Plant Nutrients and Water Losses from Fayette Silt Loam as Measured by Monolith Lysimeters," *Jour. Amer. Soc. Agron.*, 36: 249–263, 1944.

[10] Recent references concerned with the loss of nutrients in drainage will be found as follows:

Jones, R. J., "Nitrogen Losses from Alabama Soils in Lysimeters as Influenced by Various Systems of Green Manure Crop Management," *Jour. Amer. Soc. Agron.*, 34: 574–585, 1942.

Chapman, H. D., and G. F. Liebig, "Nitrogen Gains and Losses in the Growth of Legume and Non-Legume Cover Crops at Various Levels of Nitrogen Fertilizations," *Proc. Soil Sci. Soc. Amer.*, 11: 388, 1946.

Jacobson, H. G. M., *et al*, "Effect of Various Fertilizer Cations and Anions on Soil Reaction, Leaching, Nitrification of Urea and Related Characteristics," *Soil Sci.*, 65: 437–460, 1948.

For a discussion of results obtained before 1940 see Kohnke, H., *et al*, *A Survey and Discussion of Lysimeters and a Bibliography of their Construction and Performance*, Misc. Publication 372, U. S. Dept. of Agriculture, 1940.

Table 9:3. Average Annual Loss of Nutrients by Percolation through Bare and Cropped Soils. Cornell Lysimeters[11] Average of Ten and Fifteen Years Respectively (No Runoff Allowed)

Soil Condition	Pounds Per Acre per Year					
	N	P_2O_5	K_2O	CaO	MgO	SO_3
Dunkirk silty clay loam:						
Bare	69.0	Trace	86.8	557.2	104.4	132.5
Rotation	7.8	Trace	69.1	322.0	73.2	108.5
Grass	2.5	Trace	74.5	364.0	83.1	111.1
Volusia silt loam:						
Bare	43.0	Trace	77.3	452.6	68.3	88.5
Rotation	6.6	Trace	68.9	350.5	45.7	82.0

Table 9:4. Average Annual Loss of Nutrients by Percolation through Soils from Three Different Areas Using the Monolith Types of Lysimeters (Runoff Allowed from Illinois and Wisconsin Lysimeters)

Condition	Pounds per Acre per Year					
	N	P_2O_5	K_2O	CaO	MgO	SO_3
ROTATION ON A SCOTTISH SOIL[12] (AVE. 6 YEARS)						
No treatment	6.7	Trace	10.6	69.6	25.5	—
Manure and fertilizers	6.3	Trace	9.9	78.5	26.5	—
Manure, fertilizers & lime	7.9	Trace	9.2	111.4	31.2	—
UNCROPPED ILLINOIS SOILS[13] (AVE. 3½ YEARS)						
Muscatine (well drained)	76.6	—	1.5	125.8	77.1	26.2
Cowden (poorly drained)	6.1	—	0.7	15.2	5.6	3.5
FAYETTE SILT LOAM, WISCONSIN[14] (AVE. 3 YEARS)						
Fallow	—	—	1.4	53.0	30.8	7.2
Cropped to Corn	—	—	.5	20.6	9.6	2.0

In spite of the great variability of the data from the different sources, certain features of great practical importance can be cited. In the *first* place, the amount of lime carried away by drainage usually is large for humid-region soils no matter what the soil condition or treatment may be. This, together with the loss of magnesia, accounts for the tendency of such

[11] Bizzell, J. A. and T. L. Lyon, "Composition of Drainage Waters from Lysimeters at Cornell University," *Proc. and Papers, First Internat. Cong. Soil Sci.*, II: 342–357, 1927.

Lyon, T. L. and J. A. Bizzell, *Lysimeter Experiment, IV*, Memoir 194, Cornell Univ. Agr. Exp. Sta., 1936.

[12] Hendrick, J. and H. D. Welch, "The Substances Removed by the Drainage from a Scottish Soil," *Proc. and Papers, First Internat. Cong. Soil Sci.*, II: 358–366, 1927.

[13] Stauffer, R. S., "Runoff, Percolate and Leaching Losses from Some Illinois Soils," *Jour. Amer. Soc. Agron.*, 34: 830–835, 1942.

[14] Kilmer, V. J. *et al.*, "Plant Nutrient and Water Losses from Fayette Silt Loam as Measured by Monolith Lysimeters," *Jour. Amer. Soc. Agron.*, 36: 249–263, 1944.

soils to become acid. *Secondly,* there apparently is an extremely low loss of phosphorus by leaching. This is probably due to the small amount present in the soil and the tenacity with which it is held.[15] *Thirdly,* the losses of potassium and sulfur, while appreciable, probably are not important except in certain cases.

And *fourthly,* crops markedly reduce the removal of all nutrients in drainage. This is especially important in respect to the nitrogen, the loss of which usually is very low from cropped soil. It is obviously poor management, therefore, to allow a soil to remain bare during the summer season in a humid region. Plants differ markedly, however, in their influence, grass especially reducing the drainage loss of nitrogen. This may be due in part to the root residue stimulation that the general purpose decay organisms are constantly receiving and the restraint that is thereby exerted upon nitrate accumulation. (See page 150.) Practically all of the nitrogen lost in soil drainage, be it remembered, is removed in nitrate form.

The generalizations outlined above logically lead to the question of leaching control. Can the losses, in face of the fact that the removal of excess water must be facilitated, be in any way reduced? Only one suggestion of any moment can be made for field soils and this is clearly apparent from the data quoted. Keep a crop on the land as much as possible since less water passes through cropped soils, especially when sodded, than through soils that are bare. Moreover, crops undoubtedly appropriate some nutrients that otherwise might go down and perhaps out of the soil in drainage. Also, as already explained, sod crops encourage a rather effective tie-up of soil nitrogen. (See page 178.) Beyond this, little more can be suggested. Obviously it is impossible to adequately drain humid-region soils and yet hold the leaching losses, especially of lime and magnesia, at negligible levels.

Leaching vs. crop removal. One more feature of particular interest in respect to leaching losses remains—their magnitude relative to the corresponding removals by crops occupying the land. Such a comparison can be made only in a very tentative way by postulating the drainage losses from a representative humid-region silt loam and the nutrient removals on the average due to crops grown in rotation on such a soil. While the

[15] It is probable that present day analytical methods would have shown more than a trace of phosphorus in the drainage waters of some of the earlier experiments, especially if the leachates had come from fertilized sandy soils.

figures suggested (Table 9:5) are themselves open to criticism, the conclusions drawn are valid at least in a broad way.

Table 9:5. A comparison of the Average Annual Loss of Nutrients by Drainage from a Representative Humid-Region Silt Loam, Cropped to a Standard Rotation, with the Nutrients Removed by an Average Rotation Crop

	Pounds per Acre, Annually					
Losses	N	P_2O_5	K_2O	CaO	MgO	SO_3
Leached from a representative silt loam	5	Trace	20	125	30	25
Removed by average rotation crop	75	30	60	35	25	25

While comparisons of the respective losses must be made with caution, certain practical conclusions are justifiable. It is quite obvious under the conditions postulated that, ignoring possible erosion removals, most of the nitrogen, phosphoric acid, and potash is lost to the crops occupying the land. Quite the reverse is true for calcium, while magnesium and sulfur losses in the two directions are about equal.

If such generalizations are accepted, it would seem that the seriousness of leaching centers in a practical way on the high combined loss of calcium and magnesium, the increase of acidity in humid-region soils due to such losses, and the biochemical modifications that result. Were it not for leaching, we would have no lime problem and the ills that accompany high acidity would be of little moment. The idea that crops in themselves and alone are primarily responsible for fertility decline is fallacious. Leaching, as well as erosion, plays its part, and it is a large one, in reducing the fertility of soils.

9:4. LAND DRAINAGE

While percolation, especially in humid regions, causes the loss of much of the rainfall received and carries away in addition many tons of soluble material, it is generally wise to facilitate it, at the same time checking as much as possible by means of crops the loss of available nutrients. The encouragement of percolation is spoken of as *land drainage*. It is the process of removing the superfluous water from the soil profile, especially from its surface layer and upper subsoil, as rapidly as possible. While the drainage of swamps and the reclamation of overflow areas are urgent, the drainage of lands already under tillage is often much more important.

Practical farm drainage is paramount in almost every community, even in arid regions, especially where irrigation is practiced.

9:5. TYPES OF DRAINAGE—TILE DRAINS

Two general types of drains are in use, *open* and *closed.* Ditch drainage represents the first group. Ditches have the advantage of large capacity and are able to carry water at a low grade. On the other hand, they waste land, are ineffective and inconvenient. They encourage erosion and weed distribution, and demand some upkeep expenditure. While ditches have a place in land drainage, closed or underdrains should be used wherever possible.

Tile drains are the most reliable means of underdrainage in the majority of cases. While stone drains [16] are of value under certain conditions they must always be short and are likely to clog. Besides, their drainage is slow and rather inefficient. On silty soil, they do not remain in service for any length of time. Mole drains,[17] brush drains, box drains, and the like are recommended only for special situations.

The nature and operation of tile drain. Land tile are generally 12 or more inches long with a diameter varying with the amount of water to be carried. They are laid end to end in strings on the bottom of a trench of sufficient slope. A carefully protected outlet should be provided. The tile are then covered with earth, straw or surface soil often being placed directly around the tile to facilitate the entrance of the water. The superfluous water enters the tile through the joints, mostly from the sides and bottom.[18] As a consequence, the tops of the joints may be covered with

[16] Stone drains are built by arranging stone in a properly located and graded trench in such a manner as to provide a continuous channel or throat from the upper end of the drain to the lower. One of the safest modes of construction from the standpoint of clogging is to place flat stones on edge in the trench with their faces parallel to the walls of the ditch. They are capped with a layer of flat stones before the ditch is filled in. The spaces between the stones provide for the movement of the drainage water.

[17] A mole drain is simply an unwalled cylindrical channel, 3 or 4 inches in diameter, located at a satisfactory distance below the soil surface. The grade is sufficient to provide for an adequate flow of water, yet not such as to encourage erosion. This channel is established by means of a special plow equipped with a sharp blade to which is attached the *mole,* a pointed cylindrical metal plug that looks much like the shell of a field gun. As this plug is pulled through the soil, it leaves a compressed-wall channel with the proper depth and fall.

Although this type of drain is best used on heavy mineral soils, it is employed at times in peat. Needless to say, the life of such a drain is usually short compared with that of a properly installed system of tile.

[18] For flow patterns into tile drains, see Kirkham, Don, "Pressure and Streamline

paper, cloth, or even be cemented in order to prevent the entrance of silt or quicksand. The function of a tile-drain system is twofold: (1) to facilitate the collection of the superfluous water, and (2) to discharge it quickly from the land.

Drains, especially those of the closed type such as tile, are therefore, simply a means of encouraging percolation. They are most effective when the macropores are large and numerous enough and so connected as to permit the rapid downward movement of gravity water. (See Fig. 7:10.) Good drainage is thereby established on land that might otherwise maintain a temporary water table too close to the surface at certain times of the year or that might be handicapped by a permanent water table at too high a level.

Systems of tile installation. Where the land possesses considerable natural drainage, the strings of tile are laid only along the depressions. This is spoken of as the *natural* system of drainage in that the tile facilitate the quick removal of the water from the places of natural accumulation. But where the land is level or gently rolling, it often needs more uniform drainage. A *regular* system must then be installed. This may be either of the *fishbone* or *gridiron* style, or a modification or combination of the two, natural drainage being taken advantage of when possible. Where springs or seepage occur, *cutoff* systems must be devised. (See Figs. 9:4 and 9:5.)

Every regular system consists of two parts, the laterals and the main drain. The laterals are usually constructed of 3-, 4-, or 5-inch tile. These laterals should always enter the main at an angle of about 45 degrees. This causes a joining of the water currents with no loss of impetus and allows the more rapidly moving lateral streams to speed up the flow in the main drain. The size of the main depends on the amount and intensity of the rainfall, the acreage drained, and the slope. The main, of course, must be larger near the outlet than at any other point. Any good text on land drainage will present tables from which the proper size of the main drain may be determined.

The grade, or fall, necessary for the satisfactory operation of a tile-drain system varies with the system itself and the portion under consideration. The grade of the main drain may be very low, especially if the laterals deliver their water with a high velocity. In general, the grade will

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Distribution in Waterlogged Land Overlying an Impervious Layer," *Proc. Soil Sci. Soc. Amer.*, 5: 65–68, 1940.

vary from 2 to 20 inches to the hundred feet, 3 to 6 inches being more or less ideal. When the grade is reduced abruptly the installation of a silt-well may be advisable.

The depth of the tile beneath the surface of the land and the distance

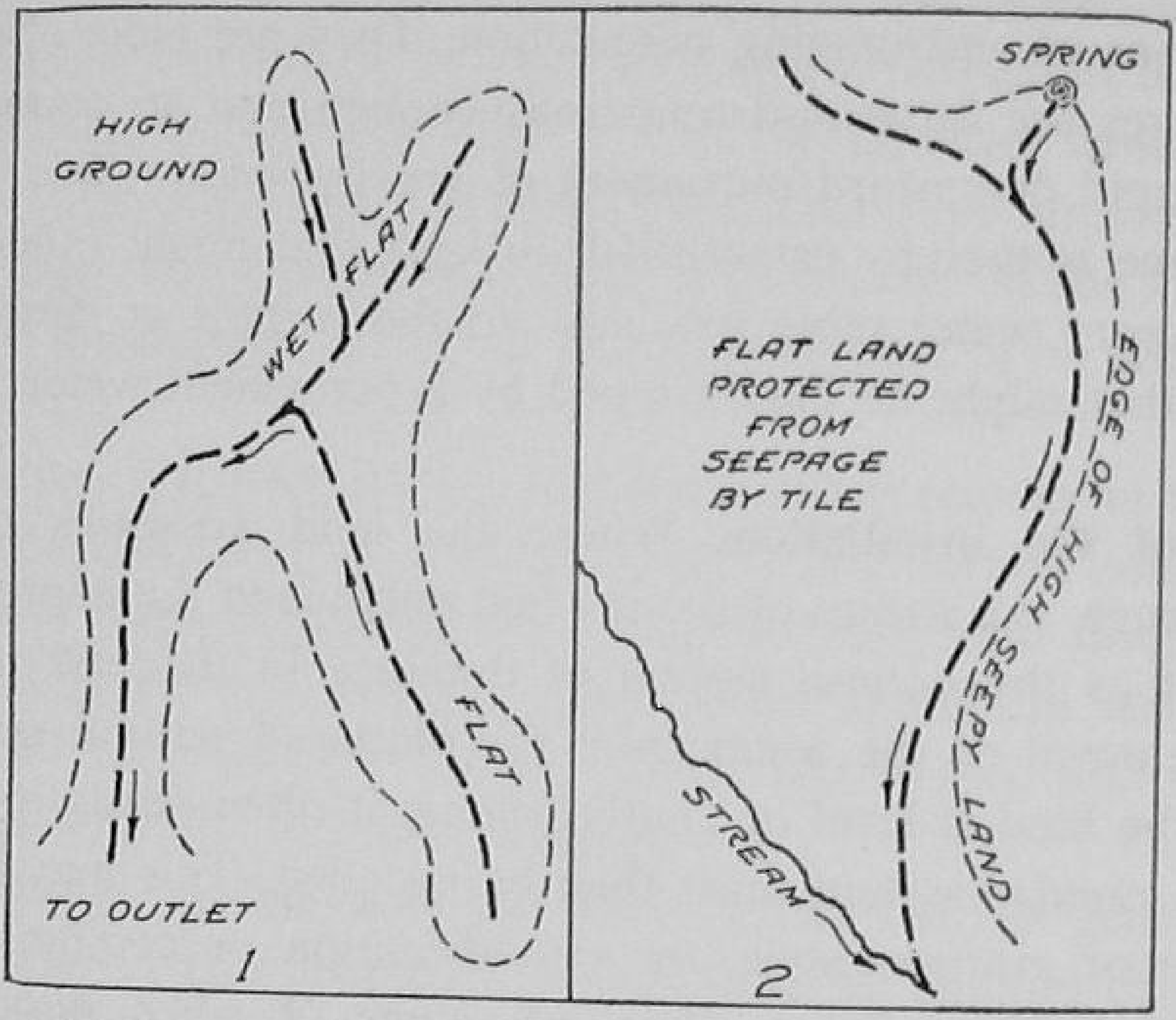

FIG. 9:4. *Natural (1) and interception (2) systems for laying tile drains. The object in both cases is to give efficient drainage at low cost.*

between laterals will vary with the nature of the soil. With sandy soils, the tile may be placed as deep as 3 or 4 feet. With clayey soils, the depth must be shallower, ranging from 15 to 30 inches. The interval between tile is also reduced as the soil becomes more compact or finer in texture. On a clayey soil, the distance between the strings is sometimes as low as 35 feet, although 50 to 75 feet is commoner.[19]

The maintenance cost of a properly installed tile-drain system is low, the only special attention usually needed being at the outlet. All outlets

[19] There are many state experiment station bulletins available on the installation of tile drains in the United States. The following books also deal with the subject:

Pickels, G. W., *Drainage and Flood Control Engineering*, McGraw-Hill Book Company, Inc., New York, 1941.

King, J. A., and W. S. Lynes, *Tile Drainage*, Mason City Brick and Tile Co., Mason City, Iowa, 1946.

Ayres, Q. C., and D. Scoates, *Land Drainage and Reclamation*, McGraw-Hill Book Company, Inc., New York, 1928.

For an excellent foreign publication, see Hudson, A. W., and H. G. Hopewell, *The Drainage of Farm Lands*, Bul. 18, Massey Agr. Col., Univ. of New Zealand, 1950.

should be well protected, so that the end tile may not be loosened and the whole system endangered by clogging with sediment. It is well to imbed the end tile in a masonry or a concrete wall or block. The last 8 or 10 feet of tile may even be replaced by a galvanized iron pipe or with sewer tile, thus insuring against damage by frost. The end tile of the system may be covered by a gate or by wire in such a way as to allow the water to flow out freely but preventing rodents from entering in dry weather.

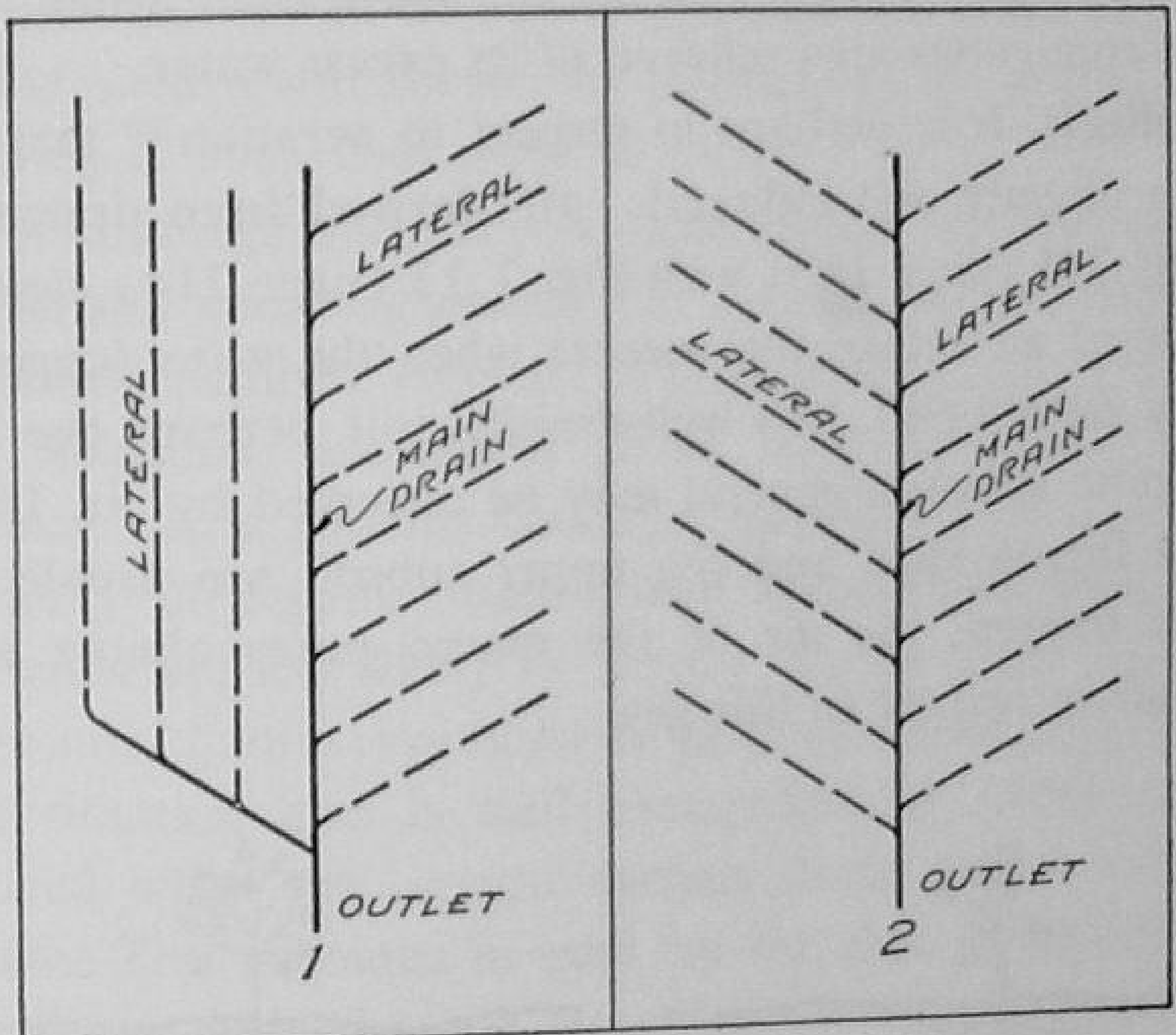

FIG. 9:5. *Gridiron (1) and fishbone (2) systems for laying tile drains. Drainage on heavy level land can be effected only by a uniform layout system.*

9:6. BENEFITS OF LAND DRAINAGE

Granulation, heaving and root zone. Draining the land promotes many conditions favorable to higher plants and soil organisms. By giving a freer rein to the forces of aggregation, granulation (see page 68) is definitely encouraged. At the same time, heaving is reduced, as it is only when the soil approaches saturation with water that alternate freezing and thawing have their most disastrous effects on plant roots. It is the heaving of small grain crops and the disruption of such taprooted plants as alfalfa and sweet clover that are especially feared. Also, drainage, by quickly lowering the water table at critical times, maintains a sufficiently deep and effective root zone (Fig. 9:6). By this means, the quantity of nutrients available to plants is maintained at a higher level.

Soil temperature. The removal of excess water also lowers the specific heat of soil, thus reducing the energy necessary to raise the temperature of the layers thus drained. At the same time, surface evaporation, which has a cooling effect, may be reduced. The two effects together tend to make the warming of the soil easier. The converse of the old saying that in the spring "a wet soil is a cold soil" applies here. Good drainage is necessary if the land is to be satisfactorily cultivated and is imperative in the spring if the soil is to warm up rapidly and properly. At this season of the year, an inadequately drained surface soil may be from 5° to 15° F. cooler than a contiguous area relieved of its excess water.

Aeration effects. It is perhaps in respect to aeration [20] that the greatest benefits, both directly and indirectly, are derived from drainage. A comparison of Fig. 7:5 (page 196) with Fig. 7:13 (page 214) clearly indicates the magnitude of air intake that occurs when the water-logged interstices are cleared by gravity pull. In a well-drained soil, perhaps one-half or even more of the pore space in general may be occupied by air. Under such a condition the furrow-slice and the upper subsoil are usually adequately supplied with oxygen, the air of the macro pores almost equaling the atmospheric air in respect to this gas.

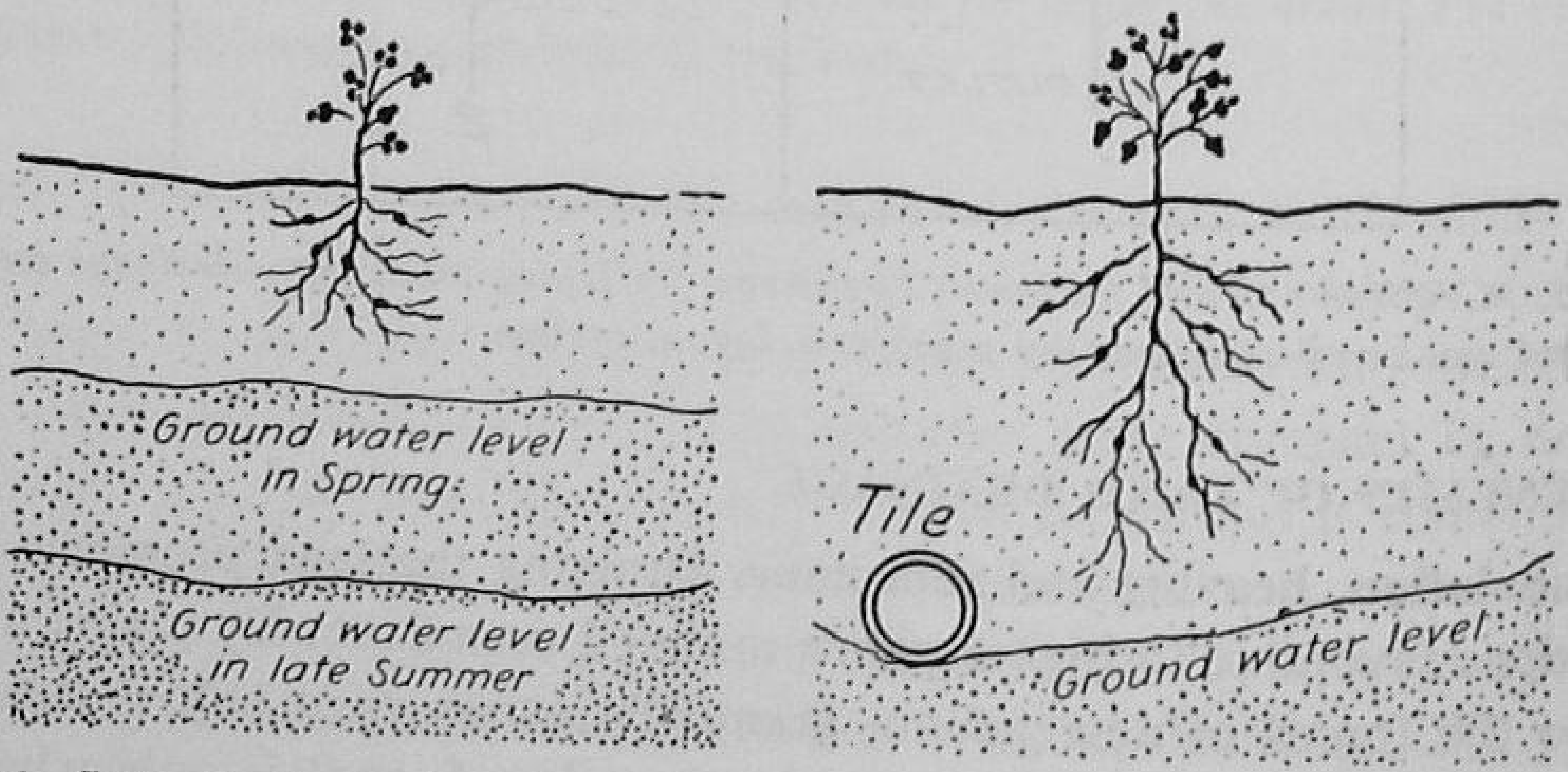

FIG. 9:6. Left, *root zone restriction that occurs when natural drainage is too slow.* Right, *lower water table and enlarged root zone that are developed by a properly installed tile drain.*

In the case of heavy surface soils, however, especially if poorly granulated, the air space may remain well below 50 per cent of the total porosity. Most of the interstices are of microsize, and they tenaciously retain water

[20] For a more detailed consideration of aeration, see Chapter 10.

against gravity. Moreover, the atmosphere that is present is likely to be too low in oxygen to supply the plant roots with amounts of this gas sufficient for their metabolic processes. Apparently, also, nutrient intake is slowed down even in the presence of abundant amounts of the necessary constituents. Here granulation as well as drainage is needed.

The situation in the subsoil may even be worse. A compact horizon with a total pore space of 30 per cent may remain almost totally saturated with water. Hence, the amount of air is low, its oxygen content restricted, and its interchange very slow. For shallow-rooted crops, this may not be so serious, but such a soil should be avoided in the location of orchards and the growing of such field crops as alfalfa.

A phase of drainage and aeration that merits separate mention is the influence upon soil microorganisms. The satisfactory coordination of their various activities requires oxygen. While some types may obtain this element by reduction, acceptable group cooperation exists only when oxygen is present in a gaseous condition and in sufficient amounts. Certainly the decay of organic matter then takes place more rapidly and toxic compounds are less likely to appear. At the same time a narrower C-N ratio results, humus synthesis is enhanced and granulation is promoted. The situation also is well exemplified by nitrification which is greatly reduced when the oxygen content drops below a certain rather high minimum. This accounts in part for the slow availability of organic nitrogen in poorly drained lands.

9:7. RUNOFF AND SOIL EROSION

In most all soils where the land is sloping or rather impervious to water, a considerable amount of the moisture received is likely to be lost by runoff. Under such conditions two considerations are important: (1) the loss of water that might otherwise enter the soil and perhaps be of use to plants, and (2) the removal of soil that usually occurs when water escapes too rapidly in this manner. This detachment and transfer of soil is spoken of as *erosion*.[21]

Effects of runoff. In some humid regions loss by runoff may rise as high as 50 or 60 per cent of the annual precipitation. In arid sections it is usually much lower, unless the rainfall is of the torrential type as it

[21] The literature on soil erosion is exceedingly voluminous. See Bennett, H. H., *Soil Conservation*, McGraw-Hill Book Company, 1939. Also see the various publications of the U. S. Soil Conservation Service.

often is in southwestern United States. While the loss of the water itself is deplorable, the erosion that accompanies it is usually even more serious, especially from the standpoint of the physical condition of the furrow slice and its fertility maintenance. The surface soil is gradually taken away. This means not only a loss of the natural fertility but also of the nutrients that have been artificially added.[22] Also it is the finer portion of this soil that is always removed first and this fraction, as already emphasized (page 51), is highest in fertility.[23]

Thus the objectives of any scheme of soil management, however good, are seriously interfered with. More than this, the furrow-slice becomes comprised of subsoil, which usually is less fertile, and the difficulty of maintaining a satisfactory physical condition is greatly enhanced. Many farmers, especially in southern United States, today are cultivating subsoils unaware that the surface soils have been stolen from under foot.

The part that water has played in the extensive development of alluvial and marine deposits has long been recognized. The concurrent destructive action that is going on in upland regions and the deplorable deposition in the lowlands have, however, been more or less disregarded until rather recently. This is partly due to the fact that erosion has been considered as more or less uncontrollable, an ill that could not be avoided.

The major factor, however, has been a lack of observation—a failure to appreciate or measure the magnitude of the insidious removal. An effect much more easy to appreciate, however, is the silting up of reservoirs which in many places is seriously reducing storage capacity and adding greatly to the expense of upkeep.[24] The early colonists of the Americas

[22] Scarseth and Chandler found that a light textured and almost level soil of Alabama during a 26 year period lost by erosion 60 per cent of the superphosphate and 82 per cent of the rock phosphate it had received during this interval. Scarseth, G. D., and W. V. Chandler, "Losses of Phosphate from a Light Textured Soil of Alabama and Its Relation to Some Aspects of Soil Conservation," *Jour. Amer. Soc. Agron.*, 30: 361–374, 1938.

[23] Neal reports that the eroded material from the Collington sandy loam (New Jersey) in comparison with the original soil contained, in total, 4.7 times as much organic matter, 5.0 times as much nitrogen, 3.1 times as much phosphorus, and 1.4 times as much potassium. Moreover, the erodate carried almost 4 times more fine material and its available potassium was 3.7 times greater than that of the original soil. Neal, O. R., "Removal of Nutrients from the Soil by Crops and Erosion," *Jour. Amer. Soc. Agron.*, 36: 601–607, 1944.

[24] Eakin, Henry M., *Silting of Reservoirs,* Technical Bulletin 524, U. S. Dept. of Agriculture, 1936. This author states that few reservoirs in the United States have a life of two hundred years, while most will completely silt up, unless periodically cleaned, in from fifty to one hundred years.

were from western Europe where erosion is not especially serious. Undoubtedly this was a contributing factor in the apathy so long existent in this part of the world in respect to erosion damage of all kinds.

Extent of erosion. The publicity that erosion losses are now receiving makes the quotation of extensive figures thereto unnecessary. Davis [25] estimates that 870 million tons of suspended material are carried yearly into the ocean by the streams of the United States—enough in ten years to cover Ohio or Kentucky with approximately 2.5 inches of sediment. And this is only a part of the soil brought down from the uplands. Much more is deposited on the way, to the detriment of the lower lands.

Bennett [26] estimates that 63,000,000 tons of plant nutrients are annually swept from the cultivated fields and pastures of the farms of the United States. This is perhaps twenty times the loss due to crop removal. The money value of such an erosion loss is probably well over $2,000,000,000 yearly and represents crop reduction values running into millions of dollars.

Later estimates by Bennett [27] indicate that perhaps upward to 50 million acres of cropland have been more or less ruined in continental United States, another 50 million reduced to a marginal state of productivity, while erosion is making rapid progress on 200 million acres more. Excluding the 100 million acres practically ruined, erosion is a serious threat to perhaps one-third or even one-half of the currently arable land in this country. (See Fig. 9:7.)

The figures for individual states are equally striking. For instance, it is estimated that perhaps 83 per cent of Alabama shows some erosion, with approximately 29 per cent rather seriously affected. The corresponding figures for Iowa are 58 per cent and 18 per cent. Although 34 per cent of New York is said to exhibit some erosion, only about 2 per cent is greatly influenced.[28]

These estimates by Bennett were made in the early years of the United States Soil Conservation Service before the erosion situation in this

[25] Davis, R. O. E., *Economic Waste from Soil Erosion*, Year Book for 1913, U. S. Dept. of Agriculture, p. 213.

[26] Bennett, H. H., "The Problem of Soil Erosion in the United States," *Proc. and Papers, First Internat. Cong. Soil Sci.*, IV: 748–757, 1939. See also *Soil Erosion a National Menace*, Circular 33, U. S. Dept. of Agriculture, 1928.

[27] Bennett, H. H., *Soil Conservation*, McGraw-Hill Book Company, Inc., New York, 1939, pp. 57–59.

[28] *Reconnaissance Erosion Survey Data*, Soil Conservation Service, U. S. Dept. of Agriculture, 1935.

country had been fully investigated and undoubtedly are too high. Nor was it realized that eroded lands, if not appreciably gullied, can in many cases be readily reclaimed.[29] Nevertheless, soil erosion ravages should not be minimized on this account. It is very serious in many sections of the United States and special precaution must be taken to insure its control. These precautions, however, are now considered as an integral part of the over-all scheme for maintaining the fertility and productivity of the land. Whether they receive major or minor attention will depend upon circumstances.[30]

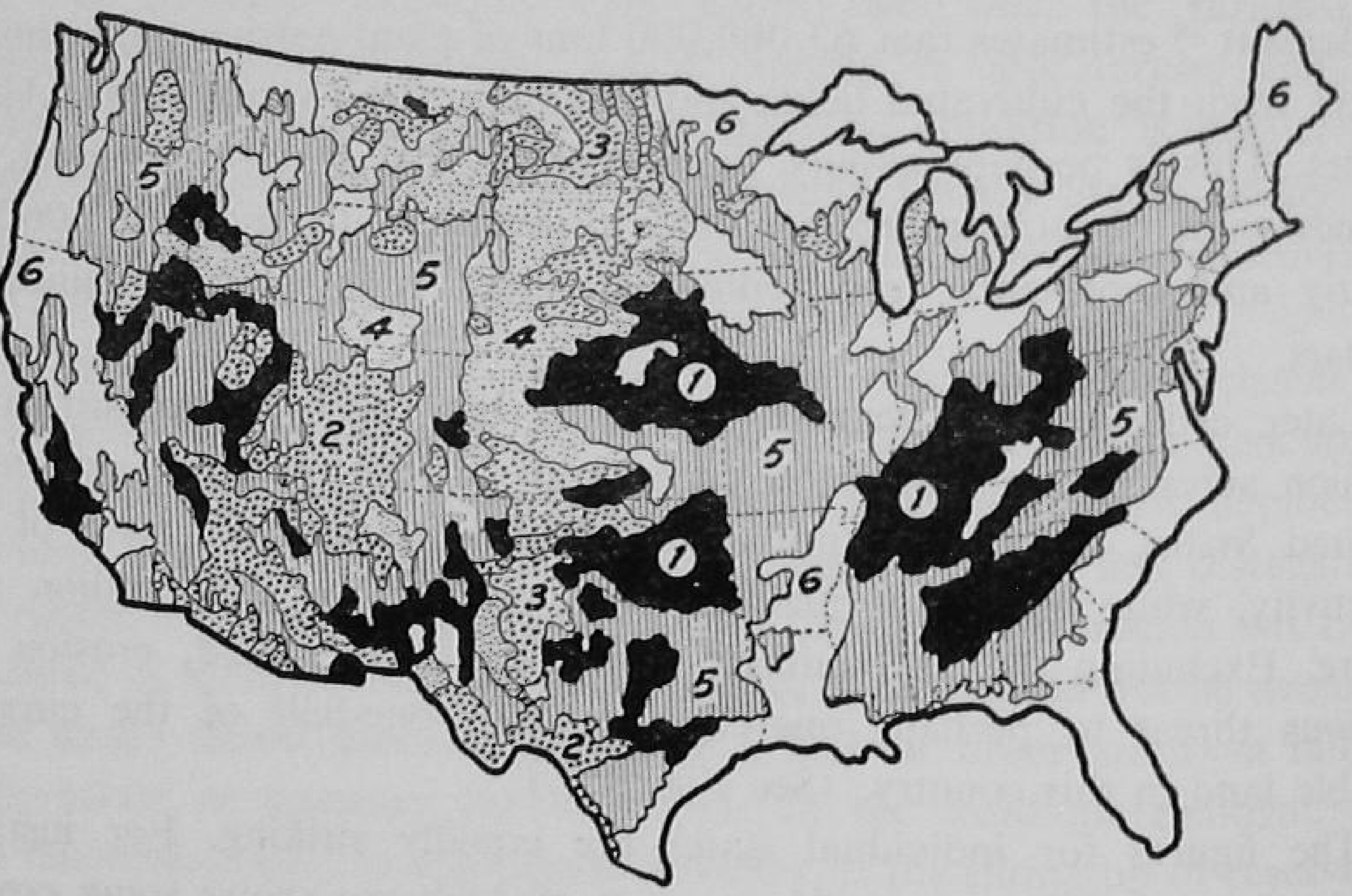

FIG. 9:7. *Erosion map of the United States. 1, severe sheets and gully erosion; 2, moderate to severe erosion of mesas and mountains; 3, moderate to severe wind erosion with some gullying; 4, moderate sheet and gully erosion with some wind action; 5, moderate sheet and gully erosion serious locally; 6, erosion rather unimportant. (After U. S. Soil Conservation Service.)*

The effects of erosion are no less serious in countries other than the United States—China, India, Syria, Palestine, to name but a few. Moreover, erosion in ancient times evidently was a menace, in Greece, in

[29] For a case, see Hays, O. E., *et al.*, "Increased Production on an Eroded Loess-derived Soil," *Jour. Amer. Soc. Agron.*, 40: 1061–1069, 1948.

[30] A rather conservative stand regarding erosion losses and soil conservation is to be found in a paper entitled "Soil Conservation," presented by Richard Bradfield before the Land Grant College Association at Kansas City, Missouri, Oct. 24, 1949. See also Baver, L. D., "How Serious Is Soil Erosion?," *Proc. Soil Sci. Soc. Amer.*, 15: 1–5, 1950.

Italy, in Syria, in North Africa, and in Persia. Perhaps the fall of empires, such as that of Rome, was hastened by the exhausting influence on agriculture of the washing away of fertile surface soils.

9:8. ACCELERATED EROSION—MECHANICS[31]

Water erosion is one of the commonest of geologic phenomena. It accounts in large part for the leveling of our mountains and the development of plains, plateaus, valleys, river flats, and deltas. The vast deposits that now appear as sedimentary rocks originated in this way. This is *normal* erosion. It operates slowly, yet inexorably. When erosion, due to man's mismanagement of the soil, exceeds this normal rate and becomes unusually destructive, it is spoken of as *accelerated.* This is the water action that especially concerns agriculture. Its mode of action is interesting.

Two steps are recognized in accelerated erosion—the *detachment* or loosening influence, which is a preparatory action, and *transportation* by floating, rolling, dragging, and splashing. Freezing and thawing, flowing water, and rain impact are the major detaching agencies. Raindrop splash and especially running water facilitate the carrying away of the loosened soil. In gullies most of the loosening and cutting is due to water flow, but on comparatively smooth soil surfaces the beating of the raindrops effect most of the detachment. The latter force is a factor in soil structure changes as well as in erosion and, until recently, has been almost entirely ignored.

Influence of raindrops. Raindrop impact exerts three important influences— (1) it detaches soil as has already been stated, (2) its beating tends to destroy granulation, and (3) its splash, under certain conditions, effects an appreciable transportation of soil. (See Fig. 9:8.) So great is the force exerted by dashing rain that soil granules not only are loosened and detached but in addition they may be beaten to pieces. Under such hammering the aggregation of a soil so exposed practically disappears. If the dispersed material is not removed by runoff it may, when drying takes place, develop into a hard crust. Such a layer is, of course, unfavorable in many ways. One example of this is the difficulty that certain seedlings, beans for instance, have in pushing through a stratum of this nature.

The protective importance of a vegetative shield, such as forest or

[31] For a discussion of the detachment and transportation phases of soil erosion, see Ellison, W. D., "Soil Erosion," *Proc. Soil Sci. Soc. Amer.*, 12: 479–484, 1947.

bluegrass, or an artificial covering, say straw or a stubble mulch, is very great indeed. Such a protection not only prevents the loss of both water and soil but also, by absorbing the energy of rain impact, it reduces degranulation to a minimum.

FIG. 9:8. *A raindrop (left) and the splash (right) that it creates when the drop strikes a wet bare soil. Such rainfall impact not only tends to destroy soil granulation and encourage sheet and rill erosion but it also effects considerable transportation by splashing. A ground cover, such as sod, will largely prevent this type of erosion. (Photo from J. H. Stallings, taken at U. S. Naval Research Laboratory.)*

Transportation of soil—splash effects. We have dealt so far only with the detachment phase of accelerated erosion. The second feature and the one usually receiving the most attention remains—that of soil transportation. In such translocation, runoff water, of course, plays the major role. So familiar are most people with the power of water to cut and carry that little more need be said regarding these capacities. In fact, so much publicity has been given to runoff that the public in general ascribe to it all of the damage done by torrential rainfall.

However, splash transportation [32] is, under certain conditions, of considerable importance. (See Fig. 9:8.) On a soil subject to easy detachment, a very heavy torrential rain may splash as much as 100 tons of soil an acre, some of the drops rising as high as 2 feet and moving horizontally perhaps 4 or 5 feet. In most cases, however, splash move-

[32] McCalla, T. M., "Influence of Some Microbial Groups on Stabilizing Soil Structure Against Falling Water Drops," *Proc. Soil Sci. Soc. Amer.*, 11: 260–263, 1946.
Ekern, P. C., and R. J. Muckenhirn, "Water Drop Impact as a Force in Transporting Sand," *Proc. Soil Sci. Soc. Amer.*, 12: 441–444, 1947.
Sreenivas, L., *et al.*, "Some Relationships of Vegetation and Soil Detachment in the Erosion Process," *Proc. Soil Sci. Soc. Amer.*, 12: 471–474, 1947.

ment is very much less. Nevertheless, especially on a slope or if the wind is blowing, splashing greatly aids and enhances runoff translocations of soil, the two together accounting for the total wash that finally occurs. Before considering methods of control let us examine the factors that influence the magnitude of accelerated erosion.

9:9. ACCELERATED EROSION—CAUSES AND RATE FACTORS

Two main factors are responsible for accelerated erosion: (1) the removal of the natural vegetative cover and (2) the undue exposure of arable soils through the use of soil exposing crops. Dense natural vegetation intercepts the rainfall and thus nullifies the impact of raindrops. In addition, both forest and natural grassland cover contribute organic matter residues. These are incorporated into the surface soil giving greater aggregate stability and absorptive capacity. Again the plant roots hold the soil in place and thus prevent erosion even when the runoff is great. Since much woodland is steep, the removal of the forest cover usually results in very rapid erosion. Even on fairly smooth uplands, the surface layer of soil often is seriously depleted before the stumps are rotted away.

A cause of serious erosion on arable land is the use of too many crops that either do not check erosion themselves or whose management and tillage greatly encourage washing. For instance, buckwheat, although it completely covers the land, is notorious in its incapacity to prevent erosion. And intertilled crops, such as corn and potatoes, especially if the rows run with the slope, tremendously augment the removal of top soil. Moreover, the loss of water that might otherwise enter the root zone is of no mean consideration.

Rate of erosion. The rate of erosion in specific cases depends on a number of factors. Those of importance are: (1) the amount, intensity, and seasonal distribution of rainfall, (2) the steepness of the slope and its length as well as the general topography of the land, (3) the size and shape of the watershed, (4) the absence or presence of channels of concentration, (5) the type of vegetative covering, and finally, (6) the nature of the soil and subsoil. Acting together these factors determine how much water enters the soil, and not only how much runs off but also, and this is of the greatest moment, the manner and rate of its removal.

Rainfall effects. Of the two phases, amount of *total rainfall* and its *intensity*, the latter is usually the more important. A heavy annual precipita-

tion received gently may cause little erosion, while a lower yearly rainfall descending torrentially may result in tremendous damage. This accounts for the marked erosion often recorded in semi-arid regions.

The *seasonal distribution* of the rainfall is also critical in determining soil erosion losses. For example, in the northern part of the United States precipitation which runs off the land in the early spring when the soils are still frozen is ineffective in bringing about erosion. The same amount of runoff a few months later, however, often carries considerable amounts of soil with it. In any climate heavy precipitation which occurs at a time of year when the soil is bare is likely to cause soil loss. Examples of such conditions are seedbed preparation time and after the harvesting of crops such as beans, sugar beets, early potatoes, etc.

Slope, topography, and channels. The greater the *degree* of *slope,* other conditions remaining constant, the greater the erosion due to increased velocity of water flow. Also more water is likely to run off. Theoretically, a doubling of the velocity enables water to move particles sixty-four times larger, allows it to carry thirty-two times more material in suspension, and makes the erosive power in total four times greater.

Moreover, the *length* of the slope is of prime importance since the greater the extension of the inclined area, the greater is the concentration of the flooding water.[33] This influence of slope is, of course, greatly modified by the size and general *topography* of the drainage area. Another modifying factor is the presence of *channels,* not only in the eroded area itself but in the watershed. The development of such channels controls the intensity of water concentration.

Effect of vegetation. Forests and grass are the best natural soil protective agencies known and are about equal in their effectiveness. But their influence varies. For instance, a forest with a heavy ground cover of organic matter and with a dense undergrowth is markedly superior to open woods with little organic accumulation. Again the kind of grass, the thickness of its stand, and the vigor of its growth greatly affect erosiveness and are of great importance in control measures.

Field crops also vary in their influence. Some, such as wheat and oats,

[33] Working with the Marshall silt loam near Clarinda in southwestern Iowa, Browning and his co-workers found that doubling the length of a 9 per cent slope increased the loss of soil by 2.6 times and the runoff water by 1.8 times. Browning, G. M., *et al., Investigations in Erosion Control and the Reclamation of Eroded Land at the Missouri Valley Loess Conservation Experiment Station, Clarinda, Iowa,* Tech. Bul. 959, U. S. Dept. of Agriculture, Soil Conservation Service, 1948.

offer considerable obstruction to surface wash, while others, especially intertilled crops, tend to encourage erosion. (See Tables 9:6 and 9:7.) A trash or stubble mulch, where it can be utilized satisfactorily with field crops, would not only check erosion but also increase infiltration, reduce evaporation, and preserve granulation.

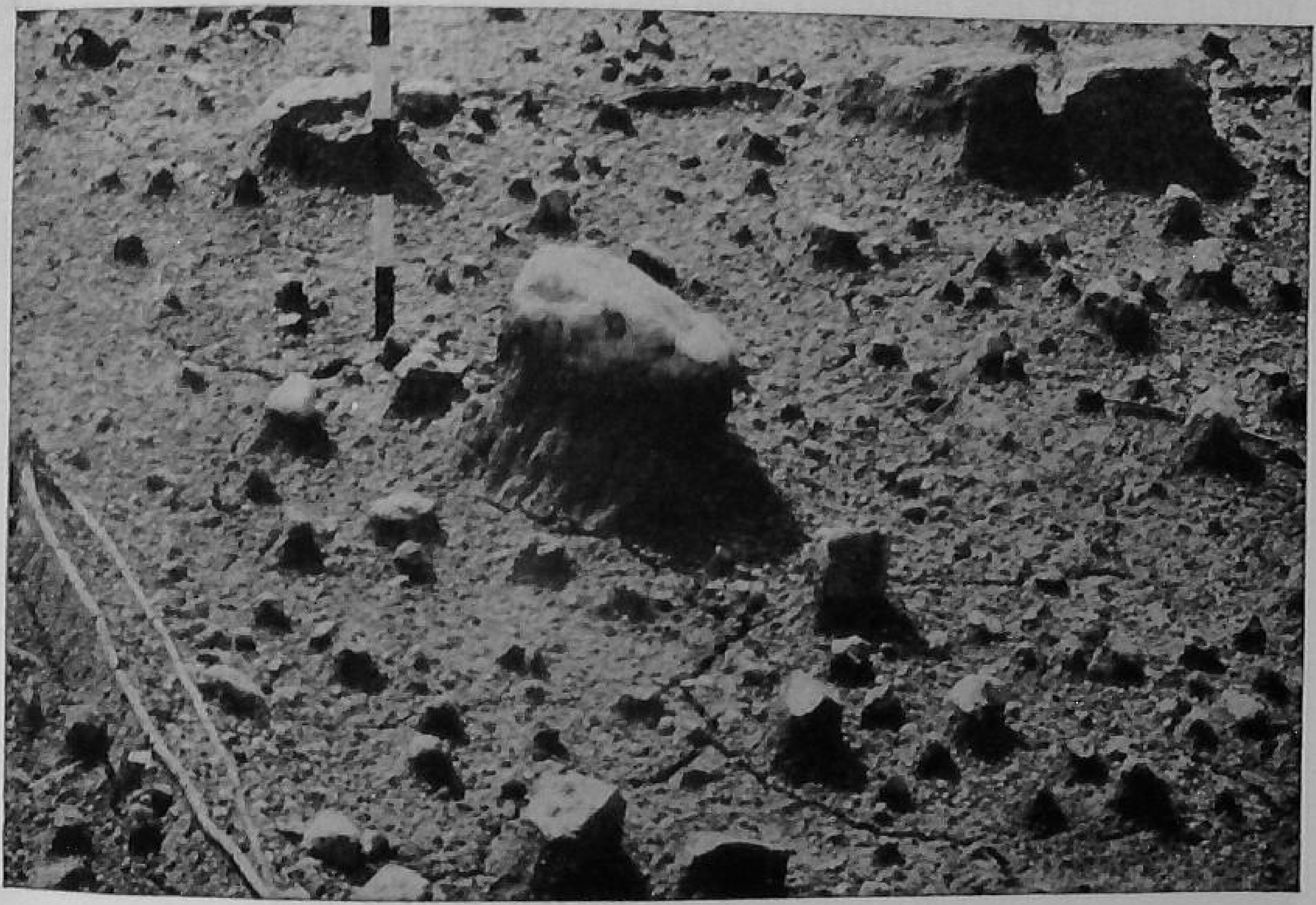

FIG. 9:9. *The perched stones and pebbles shown in the picture are mute evidence of sheet erosion—the higher the pedestals, the greater the erosion. The soil under each rock has been protected from the beating action of the rain. The pedestal in the center is about 3 inches in height. (U. S. Soil Conservation Service photo.)*

Nature of the soil. Finally, there is the nature of the soil itself. Those of latosol type (see page 346), even when clayey, are not especially susceptible to erosion because of their porous nature. In the tropics and semi-tropics, great areas of such soils occur and while some of them receive as high as 80 inches or more of rainfall annually, erosion is not serious.

On the other hand, the siliceous silty and clayey soils, which are common in continental United States and elsewhere, are greatly affected by runoff water. Heavy surface soils underlaid by impervious subsoils are especially susceptible. However, such erosion often is less serious than that which takes place when the lower horizons of the soil are loose and sandy. Once erosion channels have cut through the upper layers, the caving-in of the subsoil that occurs makes this form of wash especially destructive. The

coastal plain soils of the Southern States often exhibit this type of erosion.

9:10. TYPES OF WATER EROSION [34]

Three more or less distinct types of water erosion are generally recognized: *sheet, rill,* and *gully.* (See Figs. 9:9 and 9:10.) In the first, soil is removed more or less uniformly from every part of the slope. However, this type is often accompanied, especially on bare land newly planted or in fallow, by tiny gullies irregularly dispersed. This is *rill* erosion. But where

FIG. 9:10. *Sheet and rill erosion on an unprotected slope with serious gullying imminent if protective measures are not instituted soon. Strip cropping or even terracing, should be employed if cultivated crops are to be grown. Perhaps, better, the field could be seeded and used as pasture or meadow. In any case a diversion ditch well up the slope would be advisable. (U. S. Soil Conservation Service photo.)*

the volume of water is concentrated, the formation of large or small ravines by undermining and downward cutting occurs. This is called *gully* erosion. While all types may be serious, the losses due to sheet and rill erosion,

[34] A voluminous literature in regard to water erosion has developed in the last few years, of which a rather complete list may be obtained by writing to the Soil Conservation Service, U. S. Dept. of Agriculture, Washington, D. C.

although less noticeable, are undoubtedly the most important from the standpoint of field soil deterioration.

9:11. SHEET AND RILL EROSION—LOSSES UNDER REGULAR CROPPING

A number of different methods for the reduction and control of sheet and rill erosion may be currently utilized. Anything that will increase the absorptive capacity of the soil, such as deep plowing, surface tillage, and more organic matter, will lessen the runoff over the surface. Trash and stubble mulches are of great aid. The nature of the crops grown is an especially important factor. Intertilled crops such as corn or potatoes may actually encourage erosion, especially if the rows possess much slope. Small grains, on the other hand, tend to impede such loss.

Influence of crops. Of all field crops, however, grasses are perhaps the most efficacious in checking erosion. This is so well recognized that a sod is almost always recommended in places where serious erosion is likely to take place. The following data from Missouri (Table 9:6) indicate that sod is extremely effective on moderate slopes. The experiment cited was continued for fourteen years on a 3.7 per cent slope and under a rainfall of about 40 inches. The soil was Shelby loam and the plots were about 90 feet long.

Table 9:6. Losses from Erosion. Missouri Agricultural Experiment Station,[35] Average of Fourteen Years

Treatment	*Runoff, Per Cent of Rainfall*	*Tons of Soil Lost per Acre per Year*	*Relative Erosion, Bluegrass as 1*	*No. Yrs. to Erode 7 In. of Soil*
No crop, plowed 4 inches deep and cultivated regularly	30.7	41.64	122	24
Corn grown continuously	29.4	19.72	58	50
Wheat grown continuously	23.3	10.10	30	100
Rotation; corn, wheat & clover	13.8	2.78	8	368
Bluegrass sod continuously	12.0	0.34	1	3043

In scanning the above data, it is well first to note the large amount of soil lost especially from the bare plot and that cropped to corn. In the first case, the surface soil would disappear in only one generation; while

[35] Miller, M. F., and H. H. Krusekopf, *The Influence of Systems of Cropping and Methods of Culture on Surface Run-Off and Soil Erosion*, Research Bulletin 177, Mo. Agr. Exp. Sta., 1932.

in the other, two generations would suffice to bring the furrow-slice entirely into the subsoil.

The contrasts in respect to the different crops are just as significant. Corn allows the greatest soil loss, with wheat next. And while a good rotation exerts an appreciable erosion control, grass, as is to be expected, is most efficacious. The erosion loss here is negligible. A well-managed forest is of the same order of efficiency as grass. Since a vigorous sod is more effective than one in a less healthy condition, the fertilization and management of pastures and meadows have become an important feature of practical erosion control.

That these conclusions are sound is amply proven by data (Table 9:7) from southwestern Iowa where a Marshall silt loam (loessial) at a 9 per cent slope and with a rainfall of about 29 inches was studied. The plots were 72.6 feet long and the observations were continued for 10 years.

Table 9:7. Losses from Erosion. U. S. Soil Conservation Service Exp. Station,[36] Clarinda, Iowa. Average of Ten Years. Slope, 9 Per Cent

Treatment	*Runoff, Per Cent of Rainfall*	*Tons of Soil Lost per Acre per Year*	*Relative Erosion, Bluegrass Taken as 1*
Corn continuously	18.7	38.30	1276
Corn in rotation [37]	12.6	18.40	613
Oats in rotation [37]	9.9	10.10	336
Clover in rotation [37]	3.8	5.40	180
Rotation—corn, oats, clover	8.8	11.30	376
Alfalfa continuously	2.2	.10	3
Bluegrass continuously	1.2	.03	1

In comparing the two sets of data it is to be noted that the Iowa plots, in part because of their steeper slope, sustained the greater loss of soil. This holds for all of the treatments except continuous bluegrass and alfalfa. Yet the Iowa soil received 27 per cent less annual precipitation than the Missouri plots and only about one-half as much actual runoff occurred. Obviously many factors are involved in erosion losses.

Nutrient losses. Considering the Missouri experiments (Table 9:6) still further, it is interesting to note the amount of some of the important nu-

[36] Browning, G. M., *et al.*, *Investigation in Erosion Control and the Reclamation of Eroded Land at the Missouri Valley Loess Conservation Experiment Station, Clarinda, Iowa*, Tech. Bul. 959, U. S. Dept. of Agriculture, Soil Conservation Service, 1948.

[37] Rotation was corn, oats, and clover.

trients that were swept away by erosion. These losses are likely to be greater than one might expect since the finer particles of mineral matter, much higher in fertility than the whole soil, are sorted out and carried away. Also the humus, unless the soil is well granulated, is subject to this selective removal. This means an accelerated loss of all of the fertility elements. For comparison, tentative figures as to the nutrients withdrawn from the soil by the average crop of a standard rotation are quoted. The data, in round numbers, are shown in Table 9:8.

Table 9:8. Nutrients Removed Annually [38] in Pounds to the Acre in the Missouri Erosion Experiment Compared to the Yearly Draft of an Average Field Crop

Condition	N	P_2O_5	K_2O	CaO	MgO	SO_3
Erosion Removal						
Corn grown continuously	66	41	729	309	145	42
Rotation: corn, wheat, and clover	26	18	258	120	48	15
Crop Removal						
Average for standard rotation	75	30	60	35	25	25

While such data are not of universal application, certain conclusions may be drawn. Erosion losses, even on a 4 per cent slope, may easily exceed the removal of nutrients by crops occupying the land. This seems to be true especially for calcium, magnesium, and potassium. Moreover, the data indicate that large savings are automatically made by the common current practices that most farmers employ. Care in selecting the rotation sequence and the judicious use of legumes and other sod crops are cases in point. Other practices, equally sensible but somewhat specialized, are considered in the following paragraphs.

9:12. SHEET AND RILL EROSION—METHODS OF CONTROL

One of the most important and at the same time the most underrated means of erosion control is the maintenance of high soil fertility and productivity. The growing of bumper crops not only gives a maximum of ground cover but at the same time supplies sufficient organic matter to aid in the maintenance of this all important soil constituent. The increased permeability of soils to water under such conditions is certainly a factor of major importance. Although not usually recognized as erosion control features, the wise use of fertilizers, lime, and manure may do more to

[38] These data are for two years only.

prevent soil erosion, especially sheet and rill, than some of the more obvious mechanical means of control that are so highly rated.

In the growing of corn and similar crops, it is important that the cultivation be across the slope rather than with it. This is called *contour tillage.* On long slopes subject to sheet and rill erosion, the fields may be laid out in narrow strips across the incline, alternating the tilled crops, such as corn and potatoes with hay and grain. Water cannot attain an undue velocity on the narrow strips of cultivated land, while the hay and grain tend to markedly check the runoff flow. Such a layout is called *strip cropping* and is the basis of much of the erosion control now advocated. (See Fig. 9:11.)

FIG. 9:11. *Aerial photograph over a soil conservation district in Minnesota. In spite of contour strip cropping some erosion has occurred (near lower right-hand corner), perhaps as a result of torrential showers. (U. S. Soil Conservation Service photo.)*

When the cross strips are laid out rather definitely on the contours, the system is called *contour strip cropping.* The width of the strips will depend primarily upon the degree of slope and upon the permeability of the land and its erodibility. Table 9:9 from Gustafson [39] gives some idea as to the

[39] Gustafson, A. F., *Soils and Soil Management,* McGraw-Hill Book Company, Inc. New York, 1941, p. 207.

practicable widths. Contour strip cropping often is guarded by diversion ditches and waterways between fields. When their grade is high, they should be grass covered. This precaution is a number one rule in most erosion control.

Table 9:9. Suggested Strip Widths in Feet for Contour Strip Cropping

Slope Per Cent	*Soil Conditions*		
	Well-drained, Erodibility Low	*Medium Drainage, Erodibility Moderate*	*Poor Drainage, Erodibility High*
5	125	100	75
10	100	75	50
15	75	50	..

However, when slopes are subject to very serious erosion, they should either be reforested or kept in permanent pasture, guarding always against incipient gullying. Even in permanent pastures and in young plantations *contour furrowing* at suitable intervals often is practical as it not only aids in stabilizing the soil but also provides more water for the crop. This is especially important on droughty slopes.

When the simpler methods of checking sheet erosion on cultivated lands are inadequate, it is often advisable to resort to *terraces* constructed across the slope. These catch the water and conduct it away at a gentle grade. Opportunity is thus given for more water to soak in. The *Mangum* terrace and its modifications are now largely in vogue. Such a terrace is generally a broad bank of earth with gently sloping sides, contouring the field at a grade from 6 to 8 inches to 100 feet. It is usually formed by backfurrowing and scraping. The interval between the successive embankments depends on the slope and erodibility of the land.

Since the terrace is low and broad, it may be cropped without difficulty and offers no obstacle to cultivating and harvesting machinery. It wastes little or no land, and is quite effective if properly maintained. Where necessary, waterways are sodded. Such terracing is really a more or less elaborate type of contour strip cropping.[40]

[40] For further information see:
Bennett, H. H., *Soil Conservation*, McGraw-Hill Book Company, Inc., New York, 1939.
Ayres, Q. C., *Soil Erosion and Its Control*, McGraw-Hill Book Company, Inc., New York, 1936.

9:13. GULLY EROSION AND ITS CONTROL

Small gullies, while at first insignificant, soon enlarge into unsightly ditches or ravines. Moreover, they quickly eat into the land above, exposing its subsoil and increasing the sheet and rill erosion, already undesirably active. (See Fig. 9:10.) If small enough, such gullies may be plowed in and seeded down, using a nurse crop such as oats, barley. or wheat, which will check runoff until the grass obtains a start. Once the sod is established, it may almost entirely stop the erosion.

When the gully erosion is too active to be thus checked and the ditch is still small, dams of rotted manure or straw at intervals of 15 or 20 feet are very effective. Such dams may be made more secure by strips of wire netting staked below them. After a time the ditch may be plowed in and the site of the gully seeded and kept in sod permanently. It thus becomes a *grassed waterway,* an important feature of almost all successful erosion projects.

With moderately sized gullies, larger dams of various kinds may be utilized. These are built at intervals along the channels. If brush is used, it is piled in the gully at the desired location with the butt ends upstream. If the stakes are wired together before finally being driven down, the brush will be compressed and held firmly in place. Straw thrown above such dams will make it more effective in catching the eroded soil. Dams just as effective may be constructed from woven wire properly staked and secured. These are just a few of the details relating to this phase of water control.[41]

With very large gullies, dams of earth, concrete, or stone are often successfully used. Most of the sediment is deposited above the dam and the gully is slowly filled. The use of semi-permanent check dams, flumes, paved channels, and diversion ditches are also recommended on occasion. The only difficulty with engineering features at all extensive is that the cost may exceed the benefits derived or even the value of the land to be served. They thus may prove uneconomical.

Gustafson, A. F., *Conservation of the Soil,* McGraw-Hill Book Company, Inc., New York, 1937.

Huff, W. C., and P. R. Hoff, *Diversion Terraces and Contour Strip-Cropping,* Cornell Univ. Extension Bulletin 464, 1941.

[41] For the control of gullies of all kinds, see Ayres, Q. C., *Recommendations for the Control and Reclamation of Gullies,* Bulletin 121, Ia. Eng. Exp. Sta., Iowa State College, 1935; and Jepson, H. G., *Prevention and Control of Gullies,* Farmers' Bulletin 1813, U. S. Dept. of Agriculture, 1939.

9:14. WIND EROSION—ITS IMPORTANCE AND CONTROL

The consideration of water erosion leads naturally to the question of the movement of soil by winds. This type of soil destruction, while most common in arid and semi-arid regions, occurs to some extent in humid climates as well. It is essentially a dry-weather phenomenon and hence, in a sense, is a moisture problem. All kinds of soils and soil materials are affected and at times their more finely divided portions are carried to great heights and for hundreds of miles.

In the great dust storm of May, 1934, which originated in western Kansas, Texas, Oklahoma, and contiguous portions of Colorado and New Mexico, clouds of powdery debris were carried eastward to the Atlantic seaboard and even hundreds of miles out over the ocean. Such aeolian activity is not a new phenomenon but has been common in all geologic ages. The wind energy that gave rise to the loessial deposits now so important agriculturally in the United States and other countries, belongs in this category. (See Fig. 11:9, page 319.)

The destructive effects of wind erosion are often very serious. Not only is the land robbed of its richest soil but crops are either blown away or left to die with roots exposed or they may be covered up by the drifting debris. Even though the blowing may not be great, the cutting and abrasive effects, especially of sand, upon tender crops often is disastrous. The area in the United States subject to greatest wind action is that broad expanse called the Great Plains. Here the mismanagement of plowed lands and the lowered holding power of the range grasses due to overgrazing, have greatly encouraged wind work. In dry years, as experience has shown, the results have been most deplorable.

Areas of excessive wind erosion. Two great *dust bowls* (see Fig. 9:7) exist in the United States. One, the larger, occupies much of western Kansas, Oklahoma, and Texas, extending into southeastern Colorado and eastern New Mexico. The other, irregular and somewhat scattered, lies across the centers of three states—Nebraska, and the two Dakotas. Eastern Montana is also affected. Curiously enough, areas of severe water erosion lie contiguous to these so-called dust bowls, while gully and sheet erosion, due to torrential rainfall, are not at all uncommon within their borders.

Possibly 12 per cent of continental United States is somewhat affected by wind erosion, 8 per cent moderately so, and perhaps 2 or 3 per cent badly. While most of the damage is confined to regions of low rainfall, some

serious wind erosion occurs in humid sections. Sand dune movement is a good example. More important agriculturally, sandy soils used for vegetables are often affected by the wind. Moreover, this type of erosion is especially destructive on cultivated peats, particularly those that have been long and intensively cropped. The drying out of the cultivated and finely divided surface layers of sandy loams and peats leave them both extremely susceptible to wind drift.

Control of wind erosion. The most effective control of wind erosion is, of course, vegetative cover and on the Great Plains the seeding of plowed lands and the strengthening of the grass stands, especially by controlled grazing, are urgent. Great windbreaks have been planted in certain areas and these are already exerting a considerable influence. Unfortunately in many cases they have not been established in the areas where wind action is most serious. On cultivated lands tillage at right angles to prevalent wind direction, deep and rough furrows on land to be left bare, dam-listing, strip cropping, and the use of stubble mulches are strongly recommended.

In the case of the blowing of sands, sandy loams, and cultivated peat soils in humid regions, various control devices are used. Windbreaks and tenacious grasses and shrubs are especially effective. Picket fences and burlap screens, while less efficient as windbreaks than such trees as willows, are often preferred because they can be moved from place to place as crops and cropping practices are varied. Rye, planted in narrow strips across the field, is sometimes used on peat lands. All of these devices for wind erosion control, whether applied in arid or humid regions and whether vegetative or purely mechanical, are, after all, but phases of the broader problem of soil moisture control.

9:15. SUMMARY OF SOIL MOISTURE REGULATION

In the effective control of soil water four more or less closely related phases must be considered. They are: (1) weed transpiration, (2) surface evaporation, (3) percolation and leaching, and (4) runoff and erosion.

Weed transpiration and surface evaporation, by drawing on the available soil water, compete directly and seriously with the crop. Cultivation is the remedy commonly recommended for weeds although herbicides are being more and more utilized in connection with a suitable rotation. While cultivation may eliminate weeds and aid in the creation of a favorable tilth, the mulch thereby created apparently does not diminish evaporation from the soil surface to any degree. Such conclusions justify the cultivation of

crops only as long as the physical condition of the soil is promoted and weeds are a factor. Otherwise, cultivation is usually a waste of time as well as of water and may even be detrimental if the crop roots are greatly disturbed.

Percolation losses are serious because of the nutrients carried away, rather than because of the waste of the water. In fact, the removal of such water is necessary in order to promote soil aeration and encourage other desirable conditions. Keeping crops on the land as much as possible is the only practicable means of reducing leaching losses of nutrients. On the other hand, the detrimental influence of runoff over the surface is due to the bodily removal of soil, the loss of the water itself in some cases being of minor importance. That serious erosion should, if possible, be curbed is obvious.

The proper control of soil water has many beneficial influences other than those already noted. The regulation of the chemical and biochemical changes in the soil, the circulation of the soil air, and especially the influence on temperature are a few of the corollary relationships that may be specifically mentioned.

CHAPTER

10 Soil Air and Soil Temperature

AS WAS pointed out in Chapter 1, approximately one-half the total volume of a representative mineral surface soil is occupied by solid materials. The remaining nonsolid or pore space is occupied by water and gases. The previous three chapters (7, 8, and 9) have placed major emphasis on the soil moisture phase. They have, nevertheless, constantly reminded the reader of the interrelationship of soil air and soil water. We cannot affect one without also changing the other.

In spite of the fact that this reciprocal relationship already has been duly stressed, there are certain aspects of soil aeration which deserve separate and special consideration. This is true particularly in respect to certain plant processes.

It is logical also to include in this chapter another important physical property—the temperature of soils. Although subject to little direct control under field conditions, soil temperature is closely related to soil moisture and soil air and, of course, exerts a tremendous influence upon microorganisms and higher plants. Let us begin with the major problems of soil aeration.

10:1. SOIL AERATION DEFINED

Before considering the more detailed phases of soil aeration it may be well to define, at least in a general way, what is meant by this particular soil property. It is obvious that several definitions are possible and proper depending on the manner in which the subject is to be approached. In keeping with the edaphological viewpoint, however, soil aeration will be considered in relation to *plant growth*. Adhering to such a concept we may

look upon a well aerated soil as "one in which gases are available to growing organisms (particularly higher plants) in sufficient quantities and in the proper proportions to encourage optimum rates of the essential metabolic processes of these organisms."

A soil in which aeration is considered satisfactory must have at least two characteristics. First, sufficient space devoid of solids and water should be present. Secondly, there must be an ample opportunity for the ready movement of essential gases into and out of these spaces. Water relations largely control the *amount* of *air* space available, but the problem of adequate *air exchange* is probably a much more complicated feature. The supply of oxygen, a gas that is constantly being used in biological reactions,[1] must be continually renewed. At the same time the concentration of CO_2, the major product of these or similar reactions, must not be allowed to build up excessively in the air spaces.

10:2. SOIL AERATION PROBLEMS IN THE FIELD

Under actual field conditions there are in general two situations which may result in poor aeration in soils: (a) when the moisture content is excessively high, leaving little or no room for gases and (b) when the exchange of gases with the atmosphere is not sufficiently rapid to keep the concentration of soil gases at desirable levels. The latter may often occur even when sufficient *total air space* is available.

In the first case referred to above essentially a waterlogged condition is established. This may be quite temporary, but, nevertheless, often seriously affects plant growth. Such a situation is frequently found on poorly drained, heavy textured soils. It also occurs in soils that normally are fairly well drained if the rate of water supply at the soil surface is sufficiently rapid. A low spot in a field or even a flat area in which water tends to stand for a short while, are good examples of this condition. Such complete

[1] Two biological reactions largely account for the O_2 and CO_2 changes referred to above. They are (a) the respiration of higher plant roots and (b) the aerobic decomposition of incorporated organic residues by microorganisms. Although differing in many respects, these processes are surprisingly similar with regard to the gases involved. This similarity makes it possible to express both reactions in terms of the following very general equation:

$$[C] + O_2 \rightarrow CO_2$$

Both of the biological processes referred to result in the oxidation of carbonaceous compounds, oxygen being used up and CO_2 being evolved. Either a deficiency of O_2 or an excess of CO_2 would thus tend to cut down the rate of these reactions. In fact, both inhibitions commonly operate concurrently.

saturation of the soil with water[2] can be disastrous for certain plants in a short time, a matter of a few hours being critical in some cases. Plants which have previously been growing under conditions of good soil aeration are actually more susceptible to damage from flooding than are plants growing on soils where poor aeration has prevailed from the very start.[3]

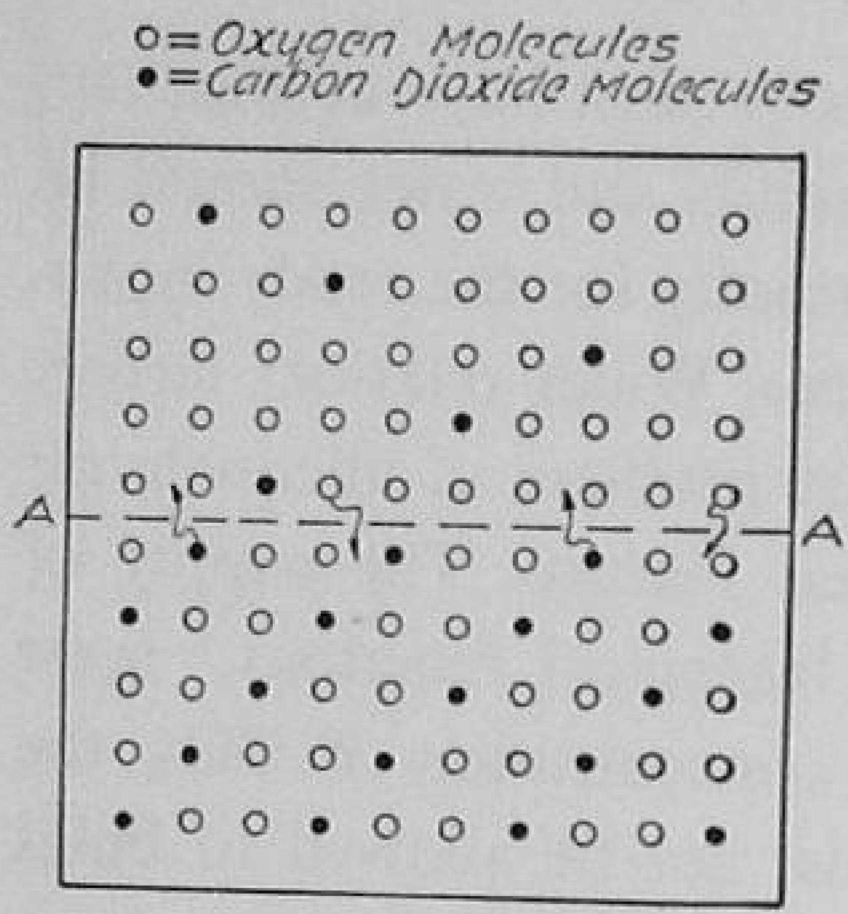

FIG. 10:1. *Diagram showing how the process of diffusion takes place. The total gas pressure is the same on both sides of boundary (A-A). The partial pressure of oxygen is greater, however, in the top portion of the container. Therefore, this gas tends to diffuse into the lower portion where fewer oxygen molecules are found. The CO_2 molecules, on the other hand, move in the opposite direction due to the higher partial pressure of this gas in the lower half. Eventually equilibrium will be established when the partial pressures of O_2 and CO_2 respectively are the same in both sides of the boundary.*

The prevention of this type of poor aeration requires the rapid removal of excess water either by land drainage or by controlled runoff. Because of the large volume of small capillary pores in some soils, even these precautions leave only a small portion of the soil volume filled with air soon after a rain. This often makes the artificial drainage of heavy soils surprisingly ineffective.

Gaseous interchange. The seriousness of inadequate *interchanges* of gases between the soil and the free atmosphere above it is dependent primarily on two factors: (a) the rate of biochemical reactions influencing the soil gases and (b) the actual rate at which each gas is moving into or out of the soil. Obviously, the more rapid the usage of O_2 and the corresponding release of CO_2, the greater will be the necessity for the exchange of gases. Factors markedly affecting these biological reactions such as temperature, organic residues, etc., undoubtedly are of considerable importance in determining air status of any particular soil. (See page 279.)

[2] It should be kept in mind that the speed with which excess water will move through a soil is determined to a large degree by the volume of the non-capillary pores. This property is much more significant in this regard than is the total porosity. The latter includes the capillary pores, most of which are too small for the rapid movement of water. This emphasizes the importance of the various factors affecting pore size which have already received attention elsewhere (page 67), as well as the inverse relationship in the amounts of soil air and soil moisture.

[3] Meyer, B. S., and D. B. Anderson, *Plant Physiology*, D. VanNostrand Company, Inc., New York, pp. 282–283.

The exchange of gases between the soil and the atmosphere above it is facilitated by two mechanisms: (a) *mass flow* and (b) *diffusion.* Mass flow of air is apparently due to pressure differences between the atmosphere and the soil air and is relatively unimportant in determining the total exchange that occurs. Its extent is determined by factors such as soil and air temperatures, barometric pressure, and wind movements.

Apparently most of the gaseous interchange in soils occurs by diffusion.[4] Through this process each gas tends to move in a direction determined by its own partial pressure.[5] (See Fig. 10:1.) This allows extensive movement from one area to another even though there is no over-all pressure gradient. Thus, even though the total soil air pressure and that of the atmosphere may be the same, a higher concentration of O_2 in the atmosphere will result in a net movement of this particular gas into the soil. An opposite movement of CO_2 and water vapor is simultaneously taking place, since the partial pressures of these two gases are generally higher in the soil air than in the atmosphere. A representation of the principles involved in diffusion is given in Figure 10:1.

In addition to being affected by partial pressure differences, diffusion seems to be directly related to the volume of pore spaces filled with air.[6] On heavy textured topsoils, especially if the structure is poor, and in compact subsoils the rate of gaseous movement is seriously slow. Moreover, such soils allow very slow penetration of water into the surface layer. This prevents the rapid replacement of air high in CO_2 and the subsequent inward movement of atmospheric air after a heavy rain or after irrigation.

10:3. COMPOSITION OF SOIL AIR

In Table 10:1 data are given showing the composition of soil air at various locations as compared to that of the atmosphere itself. These data are for topsoils only and consequently do not afford complete information as to the variabilities encountered, especially in the subsoil.[7] They do illustrate,

[4] The literature on soil aeration as it relates to plant growth has been recently summarized by Russell, M. B., A chapter in "Soil Physical Conditions and Plant Growth," *Amer. Soc. Agron.*, Monograph I, 1952.

[5] The partial pressure of a gas in a mixture is simply the pressure which this gas would exert if it alone were present in the volume occupied by the mixture. Thus, if the pressure of air is one atmosphere, the partial pressure of oxygen, which makes up about 21 per cent of the air by volume, is approximately 0.21 of an atmosphere.

[6] The literature dealing with this phase has been briefly reviewed by Blake, G. R., and J. B. Page, "Direct Measurements of Gaseous Diffusion in Soils," *Proc. Soil Sci. Soc. Amer.*, 13: 37–42, 1948.

[7] For example, under conditions of extremely poor aeration O_2 contents of soil air as low as 1 per cent have been found. See Boynton, D., *Soils in Relation to Fruit*

however, the higher CO_2 concentration and lower O_2 content of soil air as compared to that of the atmosphere. Also, there is a general inverse relationship between oxygen and carbon dioxide contents, that of O_2 decreasing as the CO_2 increases.

Although the actual differences in CO_2 contents are not impressive, comparatively speaking they are significant. Thus, when the soil air contains only 0.25 per cent CO_2 this gas is *more than 8 times* as concentrated as it is in the atmosphere. In cases where the CO_2 content becomes as high as 10 per cent, there is more than 300 times as much present as is found in the air above.

Compared to the atmosphere, soil air usually is much higher in water vapor, being essentially saturated except at or very near the surface of the soil. This fact has already been stressed in connection with the movement of water (Fig. 7:11, page 208). Also the concentration of gases such as

Table 10:1. The Composition of Soil Air at Various Locations Compared to That of the Atmosphere

Location	*Percentage by Volume*		
	O_2	CO_2	N_2[8]
Soil air:			
England[9]	20.65	0.25	79.20
Iowa[10]	20.40	0.20	79.40
New York[11]	15.10	4.50	81.40
Atmospheric air:			
England	20.97	.03	79.0

methane, hydrogen sulfide, etc. which are formed by organic matter decomposition is somewhat higher in soil air.

In addition to the free soil air already discussed, the small quantities of

Growing in New York Part XV. Seasonal and Soil Influences on Oxygen and Carbon Dioxide Levels of New York Orchard Soils, Cornell Univ. Agr. Exp. Sta. Bul., 763, 1941.

[8] The percentage of this gas was calculated and not determined.

[9] Russell, E. J., and A. Appleyard, "The Atmosphere of the Soil: Its Composition and the Causes of Variation," *Jour. Agr. Sci.*, 7: 1–48, 1915.

[10] Jodidi, S. L., and A. A. Wells, *Influence of Various Factors on Decomposition of Soil Organic Matter,* Iowa Agr. Exp. Sta., Res. Bul. No. 3, Oct., 1911.

[11] Boynton, D., *Soils in Relation to Fruit Growing in N. Y., Part XV: Seasonal and Soil Influences on Oxygen and Carbon Dioxide Levels of New York Orchard Soils,* Cornell Univ. Agr. Exp. Sta., Bul. No. 763, p. 7, June, 1941.

certain gases dissolved in the soil moisture must be considered. Also, the soil colloids are thought to hold at their surfaces small quantities of the various gases by physical adsorption. Undoubtedly, gases held in these two ways are of some importance and should not be disregarded in the study of soil aeration. Thus, oxygen so held may be utilized in oxidation reactions while dissolved carbon dioxide is of universal importance, especially in respect to soil pH and the solubility of soil minerals.

10:4. FACTORS AFFECTING THE COMPOSITION OF SOIL AIR

The composition of soil air is largely dependent upon the amount of *air space available* together with the rates of *biochemical reactions* and *gaseous interchange*. In poorly drained soils a high proportion of the pore space is filled with water. Consequently, these soils offer only small amounts of oxygen to growing organisms. When the air space becomes as low as 10–12% of the total soil volume, soil oxygen renewal is extremely slow and most plants are likely to suffer.[12]

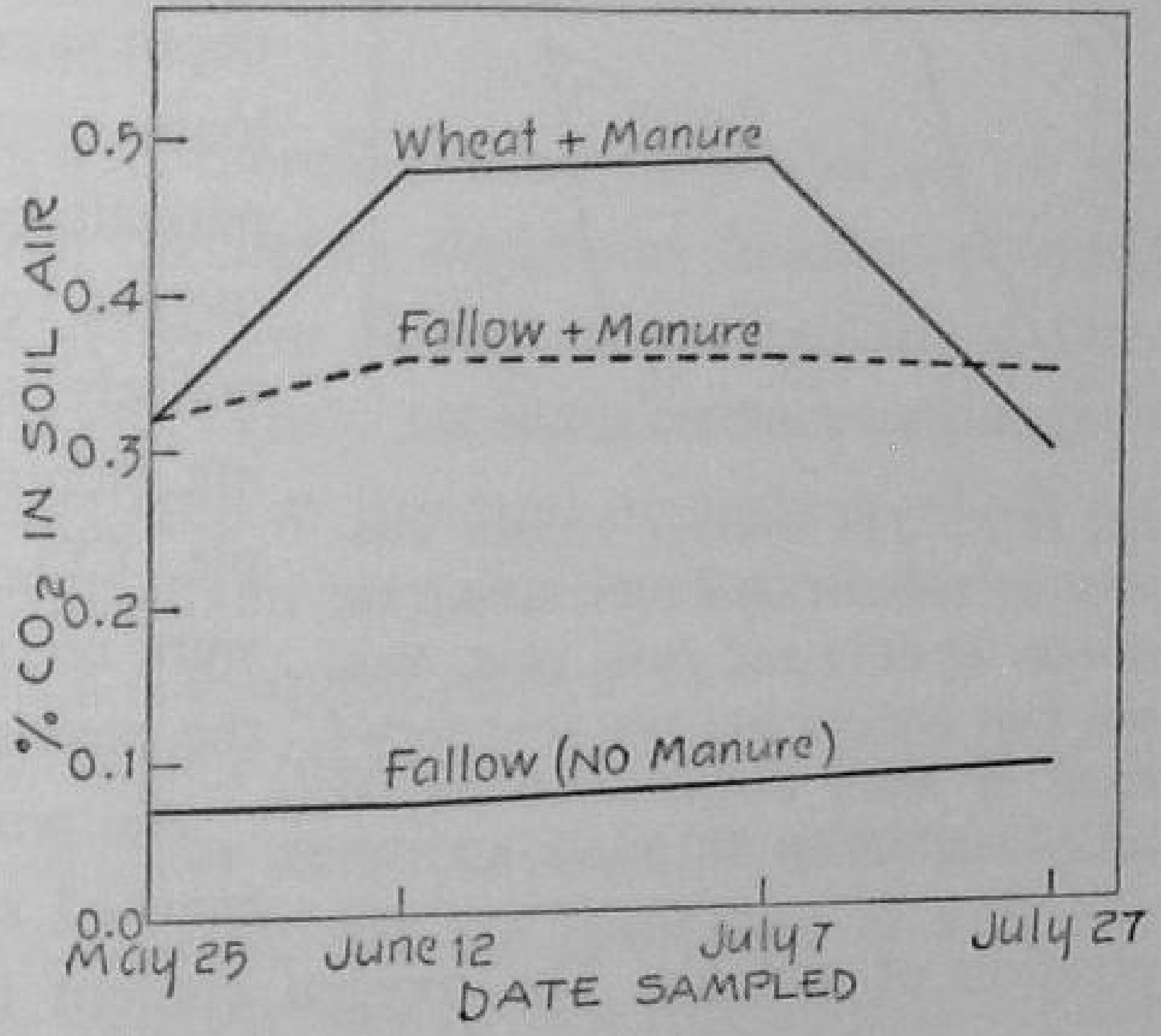

FIG. 10:2. *The carbon dioxide content of soil air at four different sampling dates, showing the effects of manure and cropping. Air samples were taken from the topsoil only. An unaccountable variation occurred in the data of June 10, hence this sampling date was omitted. (From Russell and Appleyard.)*

The concentration of both O_2 and CO_2 are definitely related to the biological activity in the soil. Microrganisms as they decompose organic residues, apparently account for the major portion of the CO_2 evolved. Incorporation of large quantities of manure, especially if moisture and temperature are optimum, will alter the soil air composition appreciably. Respiration by higher plants as well as the continuous contribution of their roots to the organic mass by sloughage should not be disregarded. These influences are well illustrated by data from Russell and

[12] See Blake, G. R., and J. B. Page, *op. cit.*, p. 41. Also Kopecky, J., "Investigations of the Relations of Water to Soil," *Proc. First Internat. Cong. Soil Sci.*, 1: 495–503, 1927.

Appleyard [13] in Figure 10:2. The effect of a growing crop and especially that of organic manures are clearly shown.

As might be expected, subsoils are usually more deficient in oxygen than are topsoils. The total pore space as well as the average size of the pores is generally much less in the deeper horizons. Boynton,[14] working on orchard sites, determined the aeration status of several soils with depth. The average oxygen contents for the months of May and June in two of the soils studied are shown in Figure 10:3.

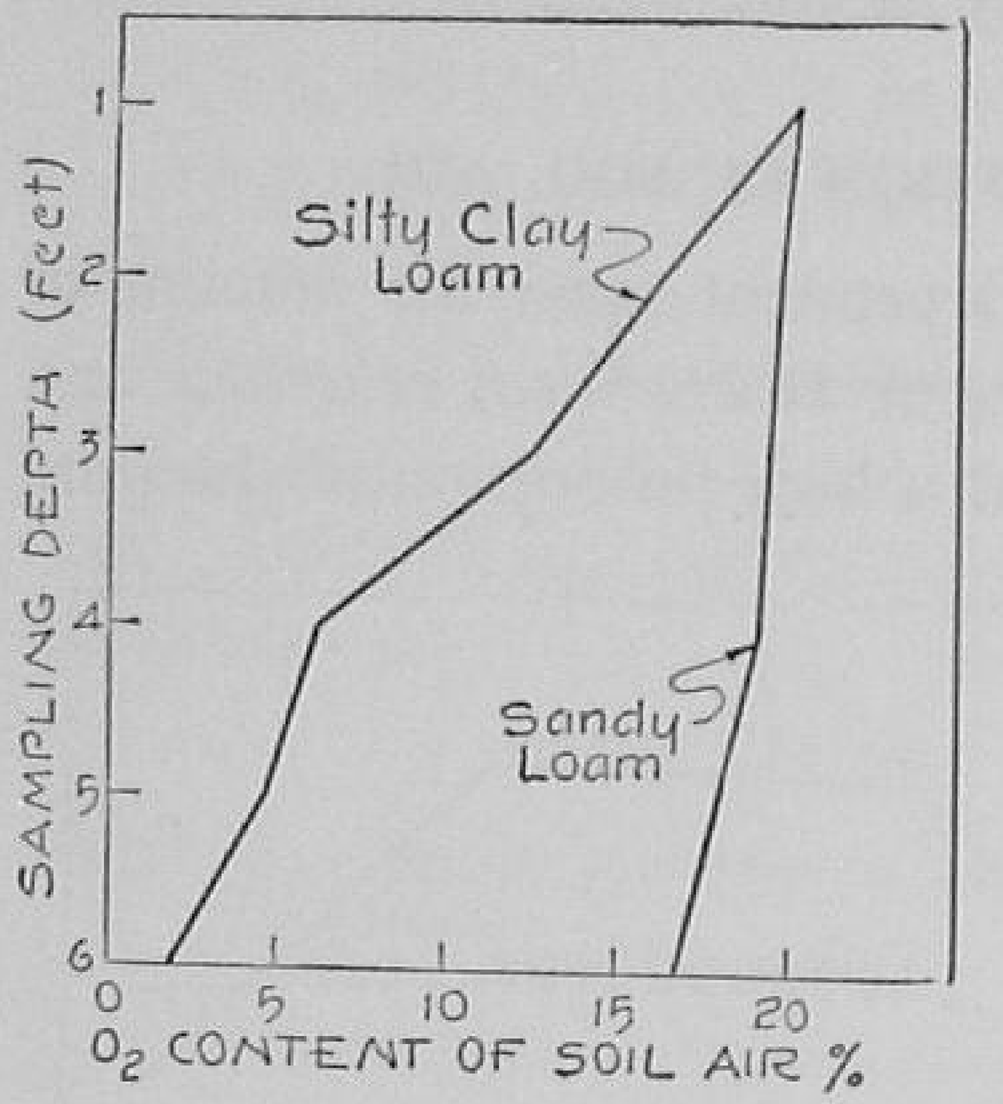

FIG. 10:3. *The average oxygen contents of two orchard soils during the months of May and June, 1938. Normal root growth and functions would occur at much deeper levels on the sandy soil. (From D. Boynton.)*

In both cases the oxygen percentage in the soil air decreased with depth, the rate of decrease being much more rapid with the heavier soil. Throughout the depth sampled the lighter textured sandy loam contained a much higher oxygen percentage. In both cases the decrease in oxygen content could be largely, but not entirely, accounted for by a corresponding increase in CO_2 content. For example, CO_2 percentages as high as 14.6 were recorded for the lower horizons of the heavier textured soil.

As would be expected, there is a marked *seasonal* variation in the composition of soil air. The oxygen content is generally higher during the summer and lower during the winter. The CO_2 content, as might be surmised, is just the reverse. Most of this variation can be accounted for by taking soil moisture and temperature differences into consideration. Everything else being equal, during those periods of the year when soil moisture is well above average a relatively high CO_2 content and low O_2 content is to be expected. High temperatures encourage this same relationship due to the more rapid microbiological activity. The dependence of soil air composition on soil moisture and temperature cannot be overemphasized.

[13] Russell, E. J., and Appleyard, A., "The Atmosphere of the Soil: Its Composition and the Causes of Variation," *Jour. Agr. Sci.*, 7: 25–26, 1915.

[14] Boynton, D., *Soils in Relation to Fruit Growing in N. Y., Part XV: Seasonal and Soil Influence on Oxygen and Carbon Dioxide Levels of New York Orchard Soils*, Cornell Univ. Agr. Exp. Sta., Bul. No. 763, pp. 26–43, June, 1941.

10:5. EFFECTS OF SOIL AERATION ON BIOLOGICAL ACTIVITIES

On microorganisms. Perhaps the most apparent effect of poor soil aeration on microbiological processes is a reduction in the rate of organic matter oxidation. This reduction seems to be associated more with a lack of O_2 than with an excess of CO_2. The slow rate of decay of plant residues in swampy areas is a somewhat exaggerated example of how a lack of oxygen prevents rapid organic matter decomposition.

All aerobic organisms are unable to function properly in the absence of gaseous oxygen. For example, special purpose bacteria such as those responsible for the oxidation of the elements nitrogen and sulfur are relatively ineffective in poorly aerated soils. This is also true for the symbiotic nitrogen fixers and for some of the nonsymbiotic *(azotobacter)* groups. (See page 465.)

The microorganism population is therefore drastically affected by soil aeration. Only the anaerobic and facultative organisms function properly under poor aeration conditions. They are able to do so because of their ability to utilize *combined* oxygen. Their activities consequently yield reduced forms of certain elements such as iron and manganese which are often toxic to higher plants. Organic toxins may also develop. Further attention will be given these effects in a subsequent section.

On activities of higher plants. Higher plants are adversely affected in at least four ways by conditions of poor aeration: (a) the growth of the plant, particularly the roots, is curtailed; (b) the absorption of nutrients and (c) also of water is generally lessened, and (d) the formation of certain inorganic compounds toxic to plant growth are favored by poor aeration. Since the last of these is considered in Section 10:6, only the first three phases will be discussed here.

The abnormal effect of insufficient aeration on root development has often been observed. With root crops such as carrots and sugar beets the influence is most noticeable. Abnormally shaped roots of these plants are common on compact, poorly aerated soils. Even with sod crops the presence of an impervious soil layer generally results in restricted growth particularly of the smaller roots. An example of this is shown in Figure 10:4, in which is pictured the root system of western wheat grass growing on a clay pan soil. It is interesting to note the lack of extensive root penetration within the impervious layer. Such restricted root systems can hardly be expected

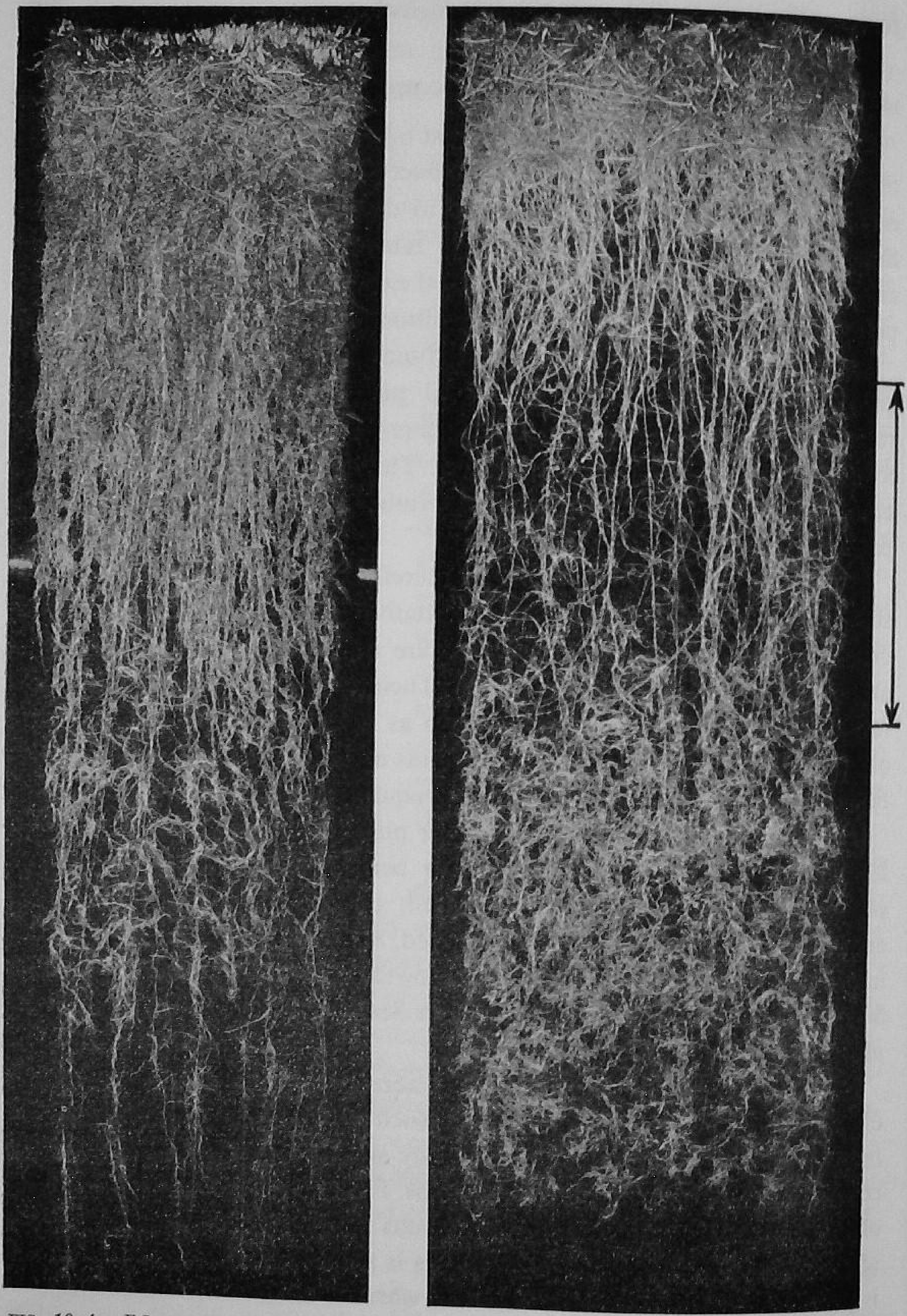

FIG. 10:4. *Effect of soil structure and aeration upon the root development of Nebraska range grass. Left—normal distribution. Right—influence of a compact, poorly aerated zone (indicated by arrow). (Photos by J. E. Weaver.)*

to effectively absorb sufficient moisture and nutrients for normal plant growth.

Apparently different levels of soil oxygen are required for the various functions of roots. For example, Boynton and co-workers[15] found that apple tree roots required at least 3 per cent oxygen in the soil air to subsist, while 5–10 per cent was sufficient for the growth of existing roots. At least 12 per cent of O_2 was required for new root growth. Their results clearly emphasize the complexity of soil aeration problems.

A deficiency of oxygen has been found to curtail nutrient and water absorption by plants.[16] The exact reasons for the effects of aeration on these two processes are not well understood. However, these processes are known to be influenced quite markedly by the rate of root respiration.[17] Apparently the *energy* of respiration is utilized in bringing about at least part of the nutrient and water absorption. Since a supply of oxygen must be available if roots are to respire normally, a deficiency of this gas naturally results in sluggish nutrient and water uptake. It is surprising as well as ironical that an oversupply of water in the soil tends to reduce the amount of water which plants will absorb.

The importance of good aeration as it relates to nutrient absorption is of considerable practical significance. Under poor aeration conditions, for example, plants exhibit nutrient deficiency symptoms on soils fairly well supplied with available nutrient elements. Also, on certain soils, improper tillage may destroy the granulation leaving conditions that lead to inefficient nutrient utilization.[18] The desirability of the frequent cultivation of heavy, poorly granulated soils when planted to row crops is undoubtedly related to this problem of nutrient uptake.

10:6. OTHER EFFECTS OF SOIL AERATION

As previously noted, anaerobic decomposition of organic materials is much slower than that occurring when ample gaseous oxygen is available.

[15] Boynton, D., J. E. DeVilliers, and W. Reuther, "Are there Different Critical Oxygen Concentrations for the Different Phases of Root Activity?" *Science*, 88: 569–70, 1938.

[16] The following are cited as reviews of the evidence in this regard:
Hoagland, D. R., *Lectures on the Inorganic Nutrition of Plants*, Chronica Botanica Co., Waltham, Mass., 1944, pp. 48–71.
Kramer, P. J., "Absorption of Water by Plants," *Bot. Rev.*, 11: 310–355, 1945.

[17] This respiration involves the oxidation of organic compounds in root cells, thus using up oxygen and releasing CO_2. (See equation bottom page 275.)

[18] See Page, J. B., C. J. Willard, and G. W. McCuen, "Progress Report on Tillage Methods in Preparing Land for Corn," *Proc. Soil Sci. Soc. Amer.*, 11: 77–80, 1946.

Moreover, the products of decomposition are entirely different. For example, the complete anaerobic decomposition of sugar occurs as follows:

$$\underset{\text{Sugar}}{C_6H_{12}O_6} \longrightarrow 3\ CO_2 + \underset{\text{Methane}}{3\ CH_4}$$

Less complete decomposition yields other products such as organic acids, which under extreme conditions may accumulate in toxic quantities. Examples of acids occurring by anaerobic decay are lactic, butyric, and citric.

When decomposed anaerobically, organic nitrogen compounds usually yield amines and gaseous nitrogen in addition to ammonia. Of course, these nitrogen compounds remain in reduced forms, not being subject to nitrification under anaerobic conditions. The absence of oxygen thus completely changes the nature of the decay processes as well as the rates at which they occur.

The chemical forms of certain elements found in soils in the oxidized and reduced states are shown in Table 10:2. In general, it can be stated that the oxidized forms are much more desirable for most of our common crops. The advantages of the oxidized states of the nitrogen and sulfur compounds have already been discussed. (See page 41.) The desirability of the higher valent forms of iron and manganese is associated with the solubility of these elements, at least in humid region soils. The reduced states, being more soluble than the oxidized forms, are often present in such quantities as to be *toxic*.[19] This is especially true if the poor aeration occurs in an acid soil.

Table 10:2. Oxidized and Reduced Forms of Several Important Elements[20]

Element	*Normal Form in Well Oxidized Soils*	*Reduced Form Found in Waterlogged Soils*
Carbon	CO_2	CH_4
Nitrogen	NO_3^-	N_2 & NH_4^+
Sulfur	$SO_4^{=}$	H_2S & $S^{=}$
Iron	Fe^{+++} (Ferric oxides)	Fe^{++} (Ferrous oxides)
Manganese	Mn^{++++} (Manganic oxides)	Mn^{++} (Manganous oxides)

[19] The insolubility of the oxidized forms of iron and manganese under alkaline conditions may result in a deficiency of these elements. Consequently, the interrelation of soil pH and aeration is very important in determining whether an excess or a deficiency of iron and manganese is apt to occur.

[20] Modified from Bradfield, R., L. P. Batjer, and J. Oskamp, *Soils in Relation to Fruit Growing in New York, IV: Significance of the Oxidation-Reduction Potential in Evaluating Soils for Orchard Purposes*, Cornell Univ. Agr. Exp. Sta. Bul. 592, 1934.

Lack of lime thus intensifies the adverse effects of poor aeration on iron and manganese toxicity.

In addition to the chemical aspect of these differences, *soil color* is markedly influenced by the oxidation status of iron and manganese. Colors such as red, yellow, reddish brown, etc., are encouraged by well-oxidized conditions. (See page 304.) More subdued shades such as grays and blues predominate if insufficient O_2 is present. These facts are made use of in field methods of determining the need for drainage. Imperfectly drained soils usually show a condition wherein alternate streaks of oxidized and reduced materials occur. This *mottled* condition indicates a zone of alternate good and poor aeration—a condition not conducive to proper plant growth.

10:7. AERATION IN RELATION TO SOIL AND CROP MANAGEMENT

In view of the overwhelming importance of soil oxygen to the growth of most of the common crop plants the question naturally arises as to the practical means of facilitating its supply. Interestingly enough, almost all methods employed for aeration control are concerned directly or indirectly with the management of soil water.

Measures that will encourage soil aeration logically fall into two categories: (1) those designed to remove excess soil moisture and (2) those concerned with the aggregation and cultivation of the soil. Each of these will be considered briefly.

Both surface- and under-drainage is essential if one expects an aerobic soil environment. Since the non-solid spaces in the soil are shared by air and water, the removal of excess quantities of the latter must take place if sufficient oxygen is to be supplied. The importance of surface runoff and tile drainage in this respect have already received attention and only need reemphasis in connection with soil aeration. (For influence of drainage see page 253.)

The maintenance of a stable soil structure should not be overlooked as a means of augmenting good aeration. Pores of macro size, usually greatly encouraged by large stable aggregates, are soon freed of water following a rain, thus allowing gases to move into the soil from the atmosphere above. Organic matter maintenance by the addition of farm manure and the growth of legumes is perhaps the most practical means of encouraging aggregate stability, which in turn will encourage good drainage and better

aeration. These features have received adequate attention elsewhere. (See page 72.)

In heavy soils, however, it is often impossible to maintain optimum aeration without resorting to the mechanical stirring of the soil by some type of cultivation. Thus, in addition to controlling weeds, cultivation in many cases has a second very important function—that of aiding soil aeration. Yields of row crops, especially those with large tap roots such as sugar beets and rutabagas, are often increased by frequent light cultivations that do not injure the fibrous roots. Part of this increase, undoubtedly, is due to aeration.

Crop-soil adaptation. In addition to the direct methods of controlling soil aeration, one more phase of soil and crop management should be mentioned—that of crop-soil adaptation. The seriousness of oxygen deficiency depends to a large degree on the crop to be grown. Alfalfa, fruit trees, and other deep rooted plants, for example, require deep well aerated soils and are quite sensitive to a deficiency of oxygen, even in the lower soil horizons. Shallow rooted plants such as alsike and ladino clovers, on the other hand, do very well on soils which tend to be poorly aerated, especially in the subsoil. These facts should not be overlooked in deciding what crops should be grown and how they are to be managed in areas where aeration problems are acute.

The dominating influence of moisture on the aeration of soils is everywhere apparent. And the control of the former means at least a partial control of the latter. This leads to a second important physical property that is at times influenced by soil water—that of soil temperature. Let us direct our attention first to some of the fundamentals concerned with this important physical characteristic.

10:8. SOIL TEMPERATURE [21]

It is universally recognized that chemical and biological activities are an energy expression. It is also known that such changes, especially the latter, will not continue with adequate intensity unless certain temperatures are maintained. The temperature of the soil is thus a factor of vital concern. For instance, nitrification does not begin until the soil reaches a tem-

[21] For a rather full edaphological discussion of soil heat, see Lyon, T. L., and H. O. Buckman, *Nature and Properties of Soils,* The Macmillan Company, New York, 1922, Chap. 9. See also Baver, L. D., *Soil Physics.* John Wiley and Sons, Inc., New York, 1940. Chap. 8.

perature of about 40°F., the most favorable limits being 80° to 90°F. Temperatures optimum for seed germination and plant growth, as might be expected, vary widely, being low for such crops as bluegrass and high for corn.

The temperature of soils in the field is dependent directly or indirectly upon at least three factors: (1) the net amount of heat the soil absorbs, (2) the heat energy required to bring about a given change in the temperature of a known amount of soil (including moisture), and (3) the energy required for changes such as evaporation which are constantly occurring at or near the surface of soils. These phases will be considered in order.

10:9. ABSORPTION AND LOSS OF HEAT

The amount of heat absorbed by soils is determined primarily by the quantity of effective *solar radiation* reaching the earth. (See Fig. 10:5.) The latter in any particular locality depends fundamentally upon climate. But the amount of energy entering the soil is, in addition, contingent largely upon other factors such as: (1) the color, (2) the slope, and (3) the vegetative cover of the site under consideration. It is well known that dark soils will absorb more energy than light-colored ones [22] and that red and yellow soils will show a more rapid temperature rise than will those that are white.[23] Observation has also shown that the nearer the angle of incident of the sun's rays approaches the perpendicular, the greater will be the absorption. As an example, a southerly slope of 20 degrees, a level soil, and a northerly slope of 20 degrees receive energy on June 21 at the 42nd parallel, north, in the proportion of 106, 100, and 81, respectively.

Wollny [24] found near Munich that the temperature of southward slopes varied with the time of year. For example, the southeasterly inclination was warmest in the early season, the southerly slope during midseason, and the

[22] This does not imply that dark-colored soils are always warmer. Actually the opposite may be true since dark-colored soils usually are high in organic matter and consequently hold large amounts of water which must also be warmed.

[23] Bouyoucos, G. J., *An Investigation of Soil Temperature*, Technical Bulletin 17, Mich. Agr. Exp. Sta., p. 30, 1913.

Lang, C., "Uber Warme-absorption und Emission des Boden," *Forsch. a.d. Gebiete d. Agr.-Physik.*, 1: 379–407, 1878.

Wollny, E., "Untersuchung über den Einfluss der Farbe des Bodens auf dessen Erwärmung," *Forsch. a.d. Gebiete d. Agr.-Physik.*, 4: 327–365, 1881.

[24] Wollny, E., "Untersuchungen über den Einfluss der Exposition auf die Erwärmung des Bodens," *Forsch. a.d. Gebiete d. Agr.-Physik.*, 1: 263–294, 1878. This publication contains a number of other papers on this subject by Wollny.

southwesterly slope in the fall. Although such a relationship will not hold universally, it indicates that slopes vary in their desirability depending on the crop to be grown. For instance, south or southeasterly slopes are often preferred by gardeners. Orchardists and foresters consider exposure an important factor not only in regard to the species or variety of tree to be grown but also in respect to sunscald and certain plant diseases.

Whether the soil is bare or covered with vegetation is another factor that markedly influences the amount of insolation received. The effect of a forest is universally recognized. Even an ordinary field crop, such as bluegrass, has a very noticeable effect, especially upon temperature fluctuations. Bare soils warm up more quickly and cool off more rapidly than those covered with vegetation, or with artificial mulches. Frost penetration during the winter is considerably greater in bare non-insulated land.

Loss of heat to atmosphere. It should be pointed out that part of the solar radiation is not permanently retained by the soil but rather is lost directly to the atmosphere. The processes which are responsible for these losses are: (1) *conduction*[25] to the atmosphere and (2) *radiation*[26] into outer space. (See Fig. 10:5.) While the contact equalization of heat between

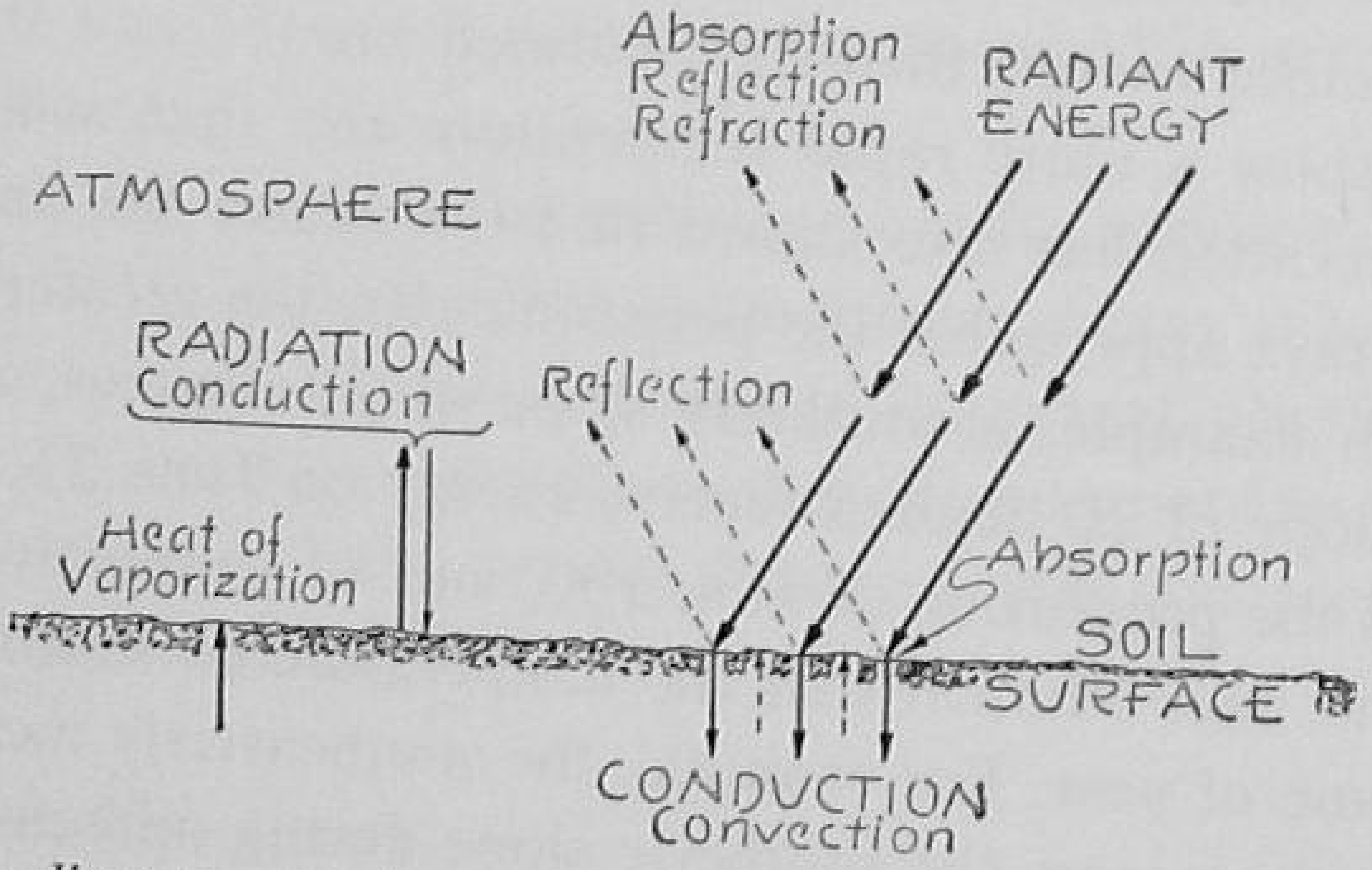

FIG. 10:5. *A diagram showing the acquisition, loss, and movement of heat in soils.*

soil and air by conduction no doubt is of considerable importance, especially if the latter is in rapid movement, radiation probably accounts for a greater loss of energy. Terrestrial bodies are continually giving off energy waves into the atmosphere. Since these rays are mostly of the infra-

[25] A molecular transfer of energy from one body to another when they are in contact or from one part of a particular body to another. The energy is conceived as communicated progressively from molecule to molecule.

[26] A transfer of energy through space by means of waves or pulsations which are transformed into heat values when they encounter an obstructing body.

red type and make no impression on the eye, they are often spoken of as *dark rays*. Suffice to say, their energy capacity is high and, as their emission is continuous, much heat is lost in this way. This accounts in part, especially during clear weather, for rapid changes in surface-soil temperatures.

10:10. AMOUNT OF ENERGY REQUIRED FOR TEMPERATURE CHANGE

Another major factor affecting the temperature relations of a soil is its specific heat.[27] This is a comparative expression of the energy necessary to raise the soil temperature a given amount. The importance of this property in soil temperature control undoubtedly is great. The mere absorption of a given amount of heat by a soil does not necessarily assure a rapid rise in temperature. Everything else being equal, a soil with a high specific heat exhibits much less rapid temperature changes than does one having a low specific heat.

Under actual field conditions the soil moisture content determines, more than any other factor, the energy required to raise the temperature of soils. For instance, the dry weight specific heat of mineral soils, in spite of variations in texture and organic matter, is about 0.20.[28] But if the moisture is advanced to 20 per cent, the specific heat of the wet mass becomes 0.33, while an increase of 30 per cent of moisture raises the wet weight specific heat to 0.38.[29] Obviously, therefore, since moisture is one of the major

[27] The specific heat of any material may be defined as its thermal capacity compared with that of water. It is expressed as a ratio of the quantity of heat required to raise the temperature of a given amount of a certain substance from 15° to 16°C compared to that required for water.

[28] The following weight specific-heat figures from Lang, Patten, and Bouyoucos are interesting:

Lang [a]		*Patten* [b]		*Bouyoucos* [c]	
Coarse sand	0.198	Sand	0.185	Sand	0.193
Limestone soil	0.249	Sandy loam	0.183	Gravel	0.204
Organic soil	0.257	Loam	0.191	Clay	0.206
Garden soil	0.276	Loam	0.194	Loam	0.215
Peat	0.477	Clay	0.210	Peat	0.252

[a] Lang, C., "Über Wärme Capacität der Bodenconstituenten," *Forsch. a.d. Gebiete d. Agr.-Physik.*, 1: 109–147, 1878.

[b] Patten, H. F., *Heat Transference in Soils*, Bureau of Soils, U. S. Dept. of Agriculture, p. 34, 1909.

[c] Bouyoucos, G. J., *An Investigation of Soil Temperature*, Technical Bulletin 17, Mich. Agr. Exp. Sta., p. 12, 1913.

[29] These figures can be easily verified. For example, consider the above soil at 20 per cent moisture content. Remembering that soil moisture is expressed as grams of water per 100 grams of soil solids, we have in this case 20 gms. H_2O with each 100

southwesterly slope in the fall. Although such a relationship will not hold universally, it indicates that slopes vary in their desirability depending on the crop to be grown. For instance, south or southeasterly slopes are often preferred by gardeners. Orchardists and foresters consider exposure an important factor not only in regard to the species or variety of tree to be grown but also in respect to sunscald and certain plant diseases.

Whether the soil is bare or covered with vegetation is another factor that markedly influences the amount of insolation received. The effect of a forest is universally recognized. Even an ordinary field crop, such as bluegrass, has a very noticeable effect, especially upon temperature fluctuations. Bare soils warm up more quickly and cool off more rapidly than those covered with vegetation, or with artificial mulches. Frost penetration during the winter is considerably greater in bare non-insulated land.

Loss of heat to atmosphere. It should be pointed out that part of the solar radiation is not permanently retained by the soil but rather is lost directly to the atmosphere. The processes which are responsible for these losses are: (1) *conduction*[25] to the atmosphere and (2) *radiation*[26] into outer space. (See Fig. 10:5.) While the contact equalization of heat between

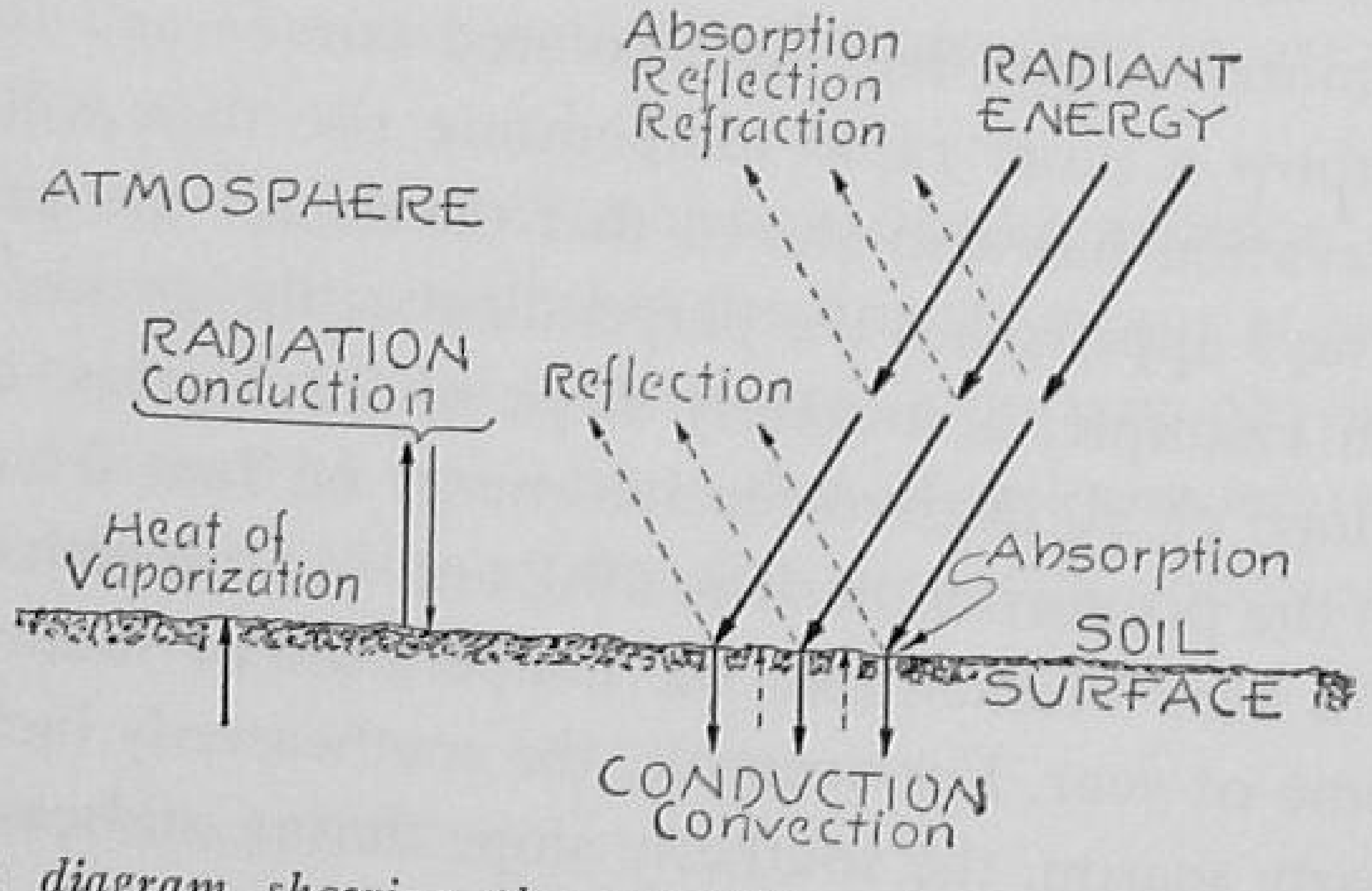

FIG. 10:5. *A diagram showing the acquisition, loss, and movement of heat in soils.*

soil and air by conduction no doubt is of considerable importance, especially if the latter is in rapid movement, radiation probably accounts for a greater loss of energy. Terrestrial bodies are continually giving off energy waves into the atmosphere. Since these rays are mostly of the infra-

[25] A molecular transfer of energy from one body to another when they are in contact or from one part of a particular body to another. The energy is conceived as communicated progressively from molecule to molecule.

[26] A transfer of energy through space by means of waves or pulsations which are transformed into heat values when they encounter an obstructing body.

red type and make no impression on the eye, they are often spoken of as *dark rays.* Suffice to say, their energy capacity is high and, as their emission is continuous, much heat is lost in this way. This accounts in part, especially during clear weather, for rapid changes in surface-soil temperatures.

10:10. AMOUNT OF ENERGY REQUIRED FOR TEMPERATURE CHANGE

Another major factor affecting the temperature relations of a soil is its specific heat.[27] This is a comparative expression of the energy necessary to raise the soil temperature a given amount. The importance of this property in soil temperature control undoubtedly is great. The mere absorption of a given amount of heat by a soil does not necessarily assure a rapid rise in temperature. Everything else being equal, a soil with a high specific heat exhibits much less rapid temperature changes than does one having a low specific heat.

Under actual field conditions the soil moisture content determines, more than any other factor, the energy required to raise the temperature of soils. For instance, the dry weight specific heat of mineral soils, in spite of variations in texture and organic matter, is about 0.20.[28] But if the moisture is advanced to 20 per cent, the specific heat of the wet mass becomes 0.33, while an increase of 30 per cent of moisture raises the wet weight specific heat to 0.38.[29] Obviously, therefore, since moisture is one of the major

[27] The specific heat of any material may be defined as its thermal capacity compared with that of water. It is expressed as a ratio of the quantity of heat required to raise the temperature of a given amount of a certain substance from 15° to 16°C compared to that required for water.

[28] The following weight specific-heat figures from Lang, Patten, and Bouyoucos are interesting:

Lang [a]		*Patten* [b]		*Bouyoucos* [c]	
Coarse sand	0.198	Sand	0.185	Sand	0.193
Limestone soil	0.249	Sandy loam	0.183	Gravel	0.204
Organic soil	0.257	Loam	0.191	Clay	0.206
Garden soil	0.276	Loam	0.194	Loam	0.215
Peat	0.477	Clay	0.210	Peat	0.252

[a] Lang, C., "Über Wärme Capacität der Bodenconstituenten," *Forsch. a.d. Gebiete d. Agr.-Physik.,* 1: 109–147, 1878.

[b] Patten, H. F., *Heat Transference in Soils,* Bureau of Soils, U. S. Dept. of Agriculture, p. 34, 1909.

[c] Bouyoucos, G. J., *An Investigation of Soil Temperature,* Technical Bulletin 17, Mich. Agr. Exp. Sta., p. 12, 1913.

[29] These figures can be easily verified. For example, consider the above soil at 20 per cent moisture content. Remembering that soil moisture is expressed as grams of water per 100 grams of soil solids, we have in this case 20 gms. H_2O with each 100

factors in respect to the heat capacity of a soil, it has much to do with the rate both of the warming up and the cooling off of soils.

10:11. HEAT OF VAPORIZATION

Soil moisture is also of major importance in determining the amount of heat used in the process of the evaporation of soil water. Vaporization is caused by an increased activity of the soil water molecules. This requires the expenditure of a certain amount of energy [30] which results in a cooling effect especially at the surface where most of the evaporation occurs. It requires 265.2 kilogram calories to evaporate 1 pound of water at 68°F. This is sufficient to lower the temperature of a cubic foot of a representative mineral soil at optimum moisture about 28°F., providing that all of the energy of evaporation comes from the soil and its water. Such a figure is, of course, empirical as only a part of the heat of vaporization comes from the soil itself. Nevertheless, it indicates the tremendous cooling influence of evaporation.

The low temperature of a wet soil is due partially to evaporation and partially to high specific heat. King [31] found during April that an undrained soil in Wisconsin ranged from 2.5°F. to 12.5°F. lower than one of the same type well drained. Drained and undrained soils at Urbana, Illinois,[32] showed maximum differences of 13.7°F., 9.0°F., and 6.2°F. at depths of 1, 2, and 4 inches respectively. The influence upon the surface layers is especially marked.

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gms. of soil. The number of calories required to raise the temperature of 20 gms. of water by 1°C. is:

$$20 \text{ (gms)} \times 1 \text{ (cal. per gm)} = 20 \text{ calories}$$

The corresponding figure for the 100 gms. of soil solids is

$$100 \text{ (gms)} \times 0.2 \text{ (cal. per gm)} = 20 \text{ calories}$$

Thus, a total of 40 calories are required to raise the temperature of 120 gms. of the moist soil by 1°C. Since the *specific heat* is the number of calories required to raise the temperature of one gram of wet soil by 1°C., in this case it is

$$\frac{40}{120} = 0.33 \text{ calories per gram.}$$

Now verify the 0.38 figure for the soil with a 30 per cent moisture content.

[30] It requires 536.6 gram calories to evaporate 1 gm. of water at 100°C., while 596.7 calories are necessary if evaporation takes place at 0°C. The calories (C) required to vaporize 1 gm. of water at any Centigrade temperature (t) may be calculated by the formula:

$$C = 596.74 - 0.601\ t.$$

[31] King, F. H., *Physics of Agriculture*, pub. by author, Madison, Wis., 1910, p. 20.

[32] Mosier, J. G., and A. F. Gustafson, *Soil Physics and Management*, J. B. Lippincott Company, Philadelphia, 1917, p. 302.

Soil color and temperature. At this point it is appropriate again to call attention to the interrelationship of soil color and soil temperature. Although dark colored soils absorbed heat readily, such soils, due to their usually high organic matter status often have high moisture contents. Under such soil conditions the evaporation and specific heat relationships become especially important. Consequently, a dark colored soil, particularly if it happens to be somewhat poorly drained, may not warm up as quickly in the spring as will a well-drained light colored soil nearby.

10:12. MOVEMENT OF HEAT IN SOILS

Before dealing with actual temperature data let us consider briefly the movement of thermal energy in the soil. As already mentioned, much of the solar insolation is dissipated into the atmosphere. Some, however, slowly penetrates the profile largely by *conduction*. (See Fig. 10:5.) While this type of movement is influenced by a number of factors, the most important is probably the moisture content of the soil layers. Heat passes from soil to water about 150 times easier than from soil to air. As the water increases in a soil, the air decreases and the transfer resistance is lowered decidedly. When sufficient water is present to join most of the soil particles, further additions will have little effect on heat conduction. Here again the major role of soil moisture comes to the fore.

The significance of conduction in respect to field temperatures is not difficult to grasp. It provides a means of temperature adjustment but, because it is slow, the subsoil changes tend to lag behind those to which the surface layers are subjected. More than this, the changes that do occur are always less in the subsoil. In temperate regions, we expect surface soils in general to be warmer in summer and cooler in winter than the subsoil, especially the lower horizons of the latter.

10:13. SOIL TEMPERATURE DATA

The temperature of the soil at any time depends on the ratio of the energy absorbed and that being lost. The constant change in this relationship is reflected in the seasonal, monthly, and daily temperatures. The accompanying data from Lincoln, Nebraska (Table 10:3) are representative of average seasonal temperatures in temperate humid climates where the rainfall is moderate.

It is apparent from these figures that the seasonal variations of soil temperature are considerable even at the lower depths. The surface layers

Table 10:3. Average Soil Temperature Readings Taken at Lincoln, Nebraska, 1890–1902, Degrees Fahrenheit [33]

		Soil at indicated Depth					
Season	*Atm. Air*	*1″*	*3″*	*6″*	*12″*	*24″*	*36″*
Winter	25.9	28.8	28.8	29.5	32.2	36.3	39.1
Spring	49.9	54.8	53.6	51.6	48.5	45.7	44.3
Summer	73.8	83.0	80.9	79.1	73.8	69.0	66.2
Autumn	53.9	56.4	57.6	57.1	57.5	59.3	60.3

vary more or less in accord with the air temperature and, therefore, exhibit a greater fluctuation than the subsoil. On the average the surface 6-inch layer of soil is warmer than the air at every season of the year, while the subsoil is warmer in autumn and winter but cooler in spring and summer due to its protected position and the lag in conduction.

This lag in temperature change in the subsoil is especially noticeable when the monthly march of soil temperature at Lincoln, Nebraska is considered. The monthly average temperatures, plotted in Figure 10:6, show a greater annual range in temperature for the surface soil than for the air. Daily data would, of course, show the greatest range for the soil air. It must be kept in mind that changes in soil temperature, except at the very surface, are gradual while the air may vary many degrees in a very short time.

The daily and hourly temperatures of the atmospheric air and the soil in temperate zones may show considerable agreement or marked divergence according to conditions. Fluctuations are, of course, more rapid in the case of air temperatures, and in temperate regions usually are greater. It is well to remember, however, that the maximum temperature of a dry surface soil may definitely exceed that of the air, possibly approaching in some cases 125° or 130°F. But in winter even surface soils do not fall greatly below freezing.

[33] Swezey, G. D., *Soil Temperatures of Lincoln, Nebraska,* 16th Annual Report, Nebr. Agr. Exp. Sta., 95–102, 1903.

Further temperature data may be found as follows:

Baver, L. D., *Soil Physics,* John Wiley and Sons, Inc., New York, 1948, pp. 304–309.

Smith, Alfred, "Seasonal Subsoil Variations," *Jour. Agr. Res.,* 44: 421–428, 1932.

Gustafson, A. F., *Soils and Soil Management,* McGraw-Hill Book Company, Inc., New York, 1941, p. 50.

Bliss, D. E., "Air and Soil Temperatures in a California Citrus Orchard," *Soil Sci.,* 58: 259–274, 1944.

With a solar control and a clear sky, the air temperature in temperate regions rises from morning to a maximum at about two o'clock. The surface soil, however, does not reach its maximum until later in the afternoon due to the usual lag. This retardation is greater and the temperature change is less as the depth increases. The lower subsoil shows little daily or weekly fluctuation, the variation, as already emphasized, being a slow monthly or seasonal change.

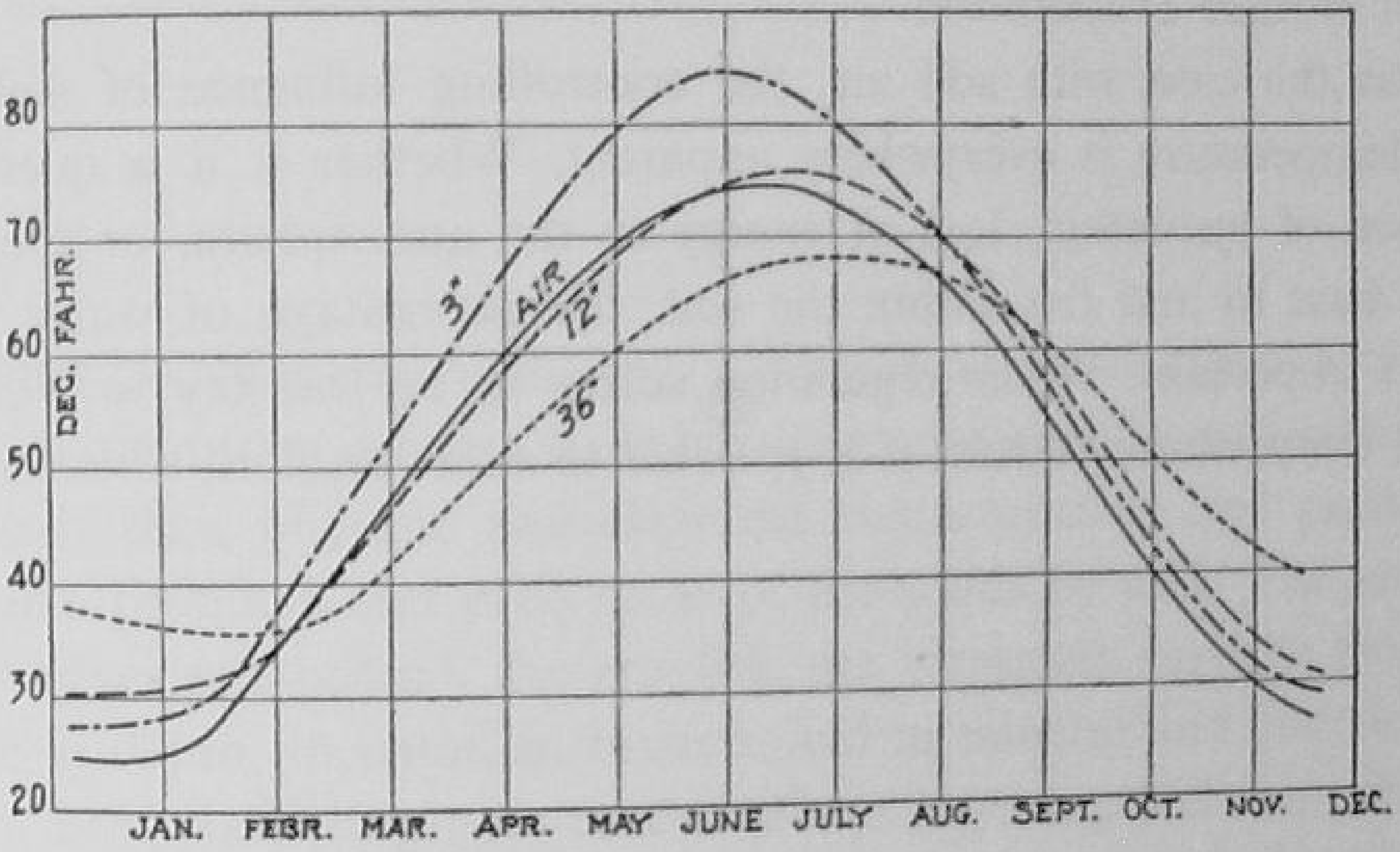

FIG. 10:6. *Average monthly air and soil temperatures at Lincoln, Nebraska (12 years). Note that the 3-inch soil layer is consistently warmer than the air above and that the 36-inch soil horizon is cooler in spring and summer, but warmer in the fall and winter than surface soil.*

10:14. SOIL TEMPERATURE CONTROL

The temperature of field soils is subject to no radical human regulation. Soil-management methods, however, especially those that influence soil moisture, do provide for small but biologically vital modifications. Let us compare briefly the temperature relations of a well-drained and a poorly-drained soil in a humid temperate region. The latter soil has a high specific heat. Therefore, large amounts of radiant energy must be absorbed to raise the soil temperature by those few extra degrees so badly needed in early spring. And since the excess water will not percolate through this soil, much of it must be removed by evaporation, another costly process in terms of heat dissipation. The low temperatures of poorly drained soils, especially in the spring, are well known. Experienced men expect a range from 6 to 12 degrees Fahrenheit lower in the surface layer than in comparable well-drained areas. Drainage is, of course, the only practicable expedient.

Besides the control relations already mentioned, there is the influence of downward moving water on soil temperature. In general, it has a cooling effect except possibly in the early spring. Precipitation is usually cooler than the soil in temperate regions, especially in the summer. But even if rain water should be 10°F. warmer than the soil, an improbable assumption, an average rain would raise the temperature of the surface 6 inches only slightly, and this would be quickly offset by the cooling effects of surface evaporation.

As was the case with soil air, the controlling influence of soil water on soil temperature is everywhere apparent. Whether it is a question of acquisition of insolation, loss of energy to the atmosphere, or the movement of heat to and fro within the soil, the percentage of water present is always important. Water regulation seems to be the key to what little practical temperature control it is possible to exert on field soils.

CHAPTER

11 The Origin, Nature, and Classification of Parent Materials

THE INFLUENCE of weathering, a manifestation of climate, is evident on all sides. Nothing escapes it. It breaks up the country rocks, it modifies or destroys their physical and chemical characteristics, and carries away the soluble products and even some of the solids as well. The unconsolidated residues left behind, the *regolith,* are extremely variable from place to place in depth, in color, in texture, and in mineral and chemical composition. But weathering goes further. It synthesizes a soil from the upper layers of this heterogeneous mass. Hence, the regolith, or at least its upper portions, may be designated as *parent material* of soils.[1]

Nor are these parent materials always allowed to remain undisturbed on the site of their development. Climatic agencies often shift them from place to place, with further grinding and leaching, until at last they are allowed to rest long enough for soil profile development to take place. A study of weathering and of the parent materials that result is not only interesting in itself, but it is also a necessary introduction to soil formation and classification. For weathering not only prepares the materials, but with endless variety and detail, it builds our soils and endows them with character.

11:1. WEATHERING PROCESSES CLASSIFIED

Weathering processes,[2] while diverse both in action and product, may be classified under two heads, mechanical and chemical. The former is often designated as *disintegration,* the latter as *decomposition.*

[1] *Parent material* may be defined as "the unconsolidated and more or less chemically weathered mineral material from which soils may be synthesized." It is the C horizon of the pedologist. (See note on page 327 for a more complete statement.)

[2] For detailed discussions of weathering, see:

1. Mechanical (disintegration)
   1. Temperature—differential expansion of minerals, frost action, and exfoliation
   2. Erosion and deposition—by water, ice, and wind
   3. Plant and animal influences
2. Chemical (decomposition)
   1. Hydrolysis
   2. Hydration
   3. Carbonation and Related Acidity Processes
   4. Oxidation
   5. Solution

11:2. MECHANICAL FORCES OF WEATHERING

Temperature effects. Variations of temperature, especially if sudden or wide, greatly influence both consolidated and fragmental materials. Rocks become heated during the day and at night often cool much below the temperature of the air. This warming and cooling is particularly effective as a disintegrating agent. Rocks are aggregates of minerals which differ in their coefficients of expansion. With every temperature change, therefore, differential stresses are set up which eventually must produce cracks and rifts, since the minerals assume their original position with difficulty. Incipient centers for further physical and chemical changes are thus established.

The presence of water, if freezing occurs, greatly increases the mechanical effects just mentioned. The force developed by the freezing of water is equivalent to about 150 tons to the square foot, an almost irresistible pressure.[3] Mountaintop rubble, talus slopes, alluvial fans, and similar formations are evidences of such action. The load of sediment carried by streams is often partially due to the prying action of temperature change, especially where crevice water is present. Nor is this influence of temperature ended when rocks are reduced to fragments. It carries onward in the parent material and finally in the resultant soil. Freezing and thaw-

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Merrill, G. P., *Rocks, Rock Weathering and Soils,* The Macmillan Company, New York, 1906.

Polynov, B. B., *The Cycle of Weathering,* Trans. by A. Muir, Thomas Murby and Company, London, 1937.

Lobeck, A. K., *Geomorphology,* McGraw-Hill Book Company, Inc., 1939.

Joffe, J. S., *Pedology,* Rutgers University Press, New Brunswick, N. J., 1949.

[3] This is equivalent to a pressure of about 142 atmospheres or over four times the negative tension exerted upon the water molecules at the liquid-air interface of a soil when its moisture content is at the hygroscopic coefficient.

ing are of great practical importance in altering the physical condition of field soils, especially if they are heavy in texture. (See page 68.)

The influence of temperature change is manifested on rocks in another way. Due to slow conduction, the outer surface of a rock mass often maintains a markedly different temperature than the inner and more protected portions. This differential heating and cooling tend to set up lateral stresses which, in time, may cause the surface layers to peel away from the parent mass. This phenomenon is spoken of as *exfoliation* and at times is markedly accelerated by the freezing of included water.

Influence of water, ice, and wind. Water, as it beats down upon the land as rain and travels oceanward, is continually shifting, sorting, and reworking unconsolidated materials of all kinds. Moreover, when loaded with such sediments, it has a tremendous cutting power as is amply demonstrated by the gorges, ravines, and valleys the country over. Some of the sediments have been carried into lakes, gulfs, and oceans, there to lie submerged for untold ages, before they serve as parent material for soils. (See page 310.) But some were deposited as stream terraces, deltas, alluvial fans, and as outwash. As such, they have been available as soil material and have provided some of our most productive lands.

Ice is an erosive and transporting agency of tremendous capacity, and next to water is perhaps the most important and spectacular physical agent of weathering. One must visit Greenland or Alaska to realize its power. While little in evidence at present in temperate regions, except on the highest mountains, ice was widely active a mere yesterday as geologic time is reckoned. The glaciation of northern North America and northern Europe is common knowledge and the erosion, transportation, and deposition that resulted are noticeable at every hand. Deposits directly by the ice and by water running from the glacial front cover thousands of square miles in the United States, Canada, Germany, Sweden, Finland, Russia and other countries. From these deposits soils of many kinds have been evolved. The importance of ice as a mechanical agent is not to be minimized. (See page 314 and ff.)

Wind has always been an important carrying agent and, when armed with fine debris, exerts an abrasive action also. Dust storms of almost continental extent may occur, with the result that tons of material are filched from one section and transferred to another. Thus, great damage is done to arable lands. (See page 271.) In ages past, fine material was thus transported on a grand scale. Millions of acres of soil, especially

in the Middle West, central and eastern Europe, in China, and elsewhere have been formed from such windborne debris. The extensive loessial deposits of the Missouri and Mississippi valleys are examples of the importance of wind as an agency in the deposition of parent materials. (See page 319.)

Plants. Simple plants, such as mosses and lichens, grow upon exposed rock, there to catch dust until a thin film of highly organic material accumulates. Higher plants sometimes exert a prying effect on rock which results in some disintegration. This is most noticeable in the case of tree roots in rocky sections. Such influences, as well as those exerted by animals, are, however, of little import in producing parent material, especially when compared to the drastic physical effects of water, ice, wind, and temperature changes. But the physical influence of biological agencies, while minimized here, assumes an important role in soil genesis and maturity. Anyone acquainted with the action of plant roots and earthworms will readily agree to this.

11:3. CHEMICAL PROCESSES OF WEATHERING

Scarcely has the disintegration of rock material begun than its decomposition usually is also apparent. This is especially noticeable in humid regions where chemical and physical processes are particularly active and markedly accelerate each other.

Hydrolysis. Of the various chemical changes that influence rocks, hydrolysis probably occurs first, especially in the weathering of the feldspars, micas, and similar minerals. Hydrolysis is a double decomposition, water being one of the reacting substances, and a hydroxide of some kind usually results. The change may be illustrated tentatively as below, using microcline as the mineral so affected. Actually, it is well to note, the reaction is much more complicated than the example might lead a person to expect.

$$\underset{\text{Microcline}}{KA1SI_3O_8} + HOH \longrightarrow \underset{\text{Acid Silicate}}{HA1Si_3O_8} + KOH$$

The acid aluminum silicate, undoubtedly more complex than herein represented, undergoes further changes, in part synthetic, and colloidal clay slowly develops therefrom. (See Fig. 4:5.) The genesis of this important constituent has already been discussed in some detail. (See page

90.) The hydroxide that results from hydrolysis cannot long exist in the presence of carbon dioxide and usually quickly changes to the carbonate or bicarbonate.

Hydration. Water functions as a weathering agent in another way—as water of combination or crystallization—and its assumption is called hydration. Many minerals, especially the feldspar, amphibole, pyroxine, and mica groups, are readily affected. They become soft and lose their luster and elasticity on the assumption of this chemically combined water, and an increase of bulk occurs. As a result, minerals so affected succumb readily to physical and chemical forces. Clay minerals are also highly hydrated, having assumed much water in the course of their synthesis. (See page 82.) Two simple yet very important examples will first be cited. One is the change of hematite to limonite by hydration alone. The other is the development of limonite when ferrous oxide undergoes hydration and oxidation.

$$\underset{\text{Hematite(red)}}{2\ Fe_2O_3} + 3\ H_2O \longrightarrow \underset{\text{Limonite(yellow)}}{2\ Fe_2O_3 \cdot 3\ H_2O}$$

$$\underset{\text{Ferrous oxide}}{4\ FeO} + 3\ H_2O + O_2 \longrightarrow \underset{\text{Limonite}}{2\ Fe_2O_3 \cdot 3\ H_2O}$$

When the products of hydration dry out due to varying weather conditions, dehydration may occur. Thus, limonite may readily be reduced to a lower hydrate or to hematite, with noticeable changes in color, especially in the latter instance.

Carbonation and other acidic processes. The disintegration and decomposition of mineral matter is greatly hastened, especially after organic influences have come into play, by the presence of certain acids, both soluble and insoluble. Of the former group carbonic acid commonly is the most important. Although it acts on a variety of different substances it tends in all cases to produce carbonates and bicarbonates. Hence, its action is commonly spoken of as carbonation.

Moreover, as clays begin to form and adsorption becomes a factor, carbonic acid is increasingly instrumental in cation exchange. This results in the substitution of hydrogen ions for adsorbed bases, especially calcium, and the development of colloidal complexes dominated by hydrogen ions (page 98). An illustrative reaction resulting in the formation of carbonates and bicarbonates is given below.

$$\text{Ca}\boxed{\begin{matrix}\text{Colloidal}\\\text{Surface}\end{matrix}} + 2\,H_2CO_3 \rightleftharpoons \begin{matrix}\text{H}\\\text{H}\end{matrix}\boxed{\begin{matrix}\text{Colloidal}\\\text{Surface}\end{matrix}} + Ca(HCO_3)_2$$

Replaceable Calcium	Carbonic Acid	Acid Clay	Bicarbonate

Small amounts of soluble organic acids, other than carbonic, may aid somewhat in the weathering processes already described. Also soluble inorganic acids may make their appearance under certain conditions. The presence of nitric acid in the rainfall from tropical thunder storms is an example of this. All of the acids mentioned other than carbonic are, however, relatively unimportant in the preparation of parent material in comparison with the influence that may at times be exerted by insoluble acid clays. Their role in respect to weathering deserves further attention.

If silicate clays are developed in the regolith under conditions whereby they may be depleted of their adsorbed bases, an acid colloidal complex will result. These insoluble clay acids seem to be able to react rather readily with such minerals as the soda-lime feldspars, the pyroxenes, the amphiboles, and other groups, robbing them of their bases and thereby changing them to acid silicates. These displaced bases are subsequently removed in drainage as carbonates and bicarbonates, thereby keeping the reaction moving to the right. Thus the formation of acid silicates is constantly encouraged. The following reaction is suggestive of what probably occurs.

$$\text{Ca(Feldspar)} + \text{H(Clay)} \rightleftharpoons \text{H(Silicate)} + \text{Ca(Clay)}$$

Ca(Feldspar)	H(Clay)	H(Silicate)	Ca(Clay)
Anorthite	acid clay	acid silicate	Ca^{++} slowly removed by cation exchange and leaching

The mechanism is simple, at least in principle, the H-ions of the acid clays replacing the bases of the fresh minerals with which they may closely contact. An acid silicate results which is subject to recrystallization, thus producing clay. Thus, "clay begets clay" by a mechanism that depends upon the removal of bases from the weathering mass of minerals by insoluble inorganic acids.

Undoubtedly the weathering of most silicate minerals is hastened by acid clays. Hence, in any discussion of the genesis of the regolith and the

development of parent materials, the possible formation of acid clays and their subsequent reactions should be given due consideration.[4]

Oxidation. Of the various chemical changes due to weathering, oxidation is usually one of the first to be noticed casually. It is particularly manifest in rocks carrying iron in the sulfide, carbonate, or silicate forms. The oxidation of the iron is indicated by a discoloration of the affected rock. The amphibole and pyroxene groups are easily influenced, until, as the process continues, these minerals waste away into hardly recognizable forms. This so weakens the rock as to allow it to crumble easily. The way is now open for more vigorous chemical changes of all kinds.

Oxidation may be illustrated, using olivine as the iron-carrying mineral. On the assumption of water, serpentine (a hydrated product) and ferrous oxide may result. The latter readily oxidizes to the ferric state. This is shown in the second reaction.

$$\underset{\text{Olivine}}{3\ MgFeSiO_4} + 2\ H_2O \longrightarrow \underset{\text{Serpentine}}{H_4Mg_3Si_2O_9} + SiO_2 + \underset{\text{Ferrous oxide}}{3\ FeO}$$

$$\underset{\text{Ferrous oxide}}{4\ FeO} + 3\ H_2O + O_2 \longrightarrow \underset{\text{Limonite}}{2\ Fe_2O_3 \cdot 3\ H_2O}$$

Solution. While weathering produces many complex compounds, it is evident that there is a considerable amount of simplification as well. And since water is universally present, solution of course occurs. Such cations as calcium, magnesium, sodium, and potassium, as well as several others, are found in the water that circulates through rocks and soil materials. These metallic ions are generally associated with such anions as chlorides, sulfates, bicarbonates, carbonates, and the like. Carbon dioxide intensifies to a marked degree the solvent action of water and, consequently, increases its power as a weathering agent. The presence of decaying organic matter, even in small amounts, is of tremendous importance in this respect.

[4] For a more detailed consideration of acid clays as weathering agents see:
Graham, E. R., "Primary Minerals of the Silt Fraction as Contributors to the Exchangeable Base Level of Acid Soils," *Soil Sci.*, 49: 277–281, 1940.
Graham, E. R., and H. C. Turley, "Soil Development and Plant Nutrition: III. The Transfer of Potassium from the Nonavailable Form as Reflected by the Growth and Composition of Soybeans," *Proc. Soil Sci. Soc. Amer.*, 12: 332–335, 1947.
Keller, W. D., "Acid Clay—A Weathering Agent," *The Scientific Monthly*, 44: 513–514, 1947. The article by Keller is a well written popular exposition.

Solution, accelerated by both mechanical and chemical means, is particularly important in that it facilitates a continual loss of constituents as weathering proceeds. A comparison of fresh rock with its weathered equivalent shows this removal to be very large, especially in humid regions. This constant downward drain accounts for the deficiencies of certain elements not only in the parent material but also in the soil to which it has given rise.[5]

On the other hand, this solution, however wasteful, is essential. The intervention of water is necessary in order that the various changes, especially hydrolysis, hydration, and carbonation, may reduce rocks to parent material and finally promote the genesis of soils. The development of the

[5] In connection with this general consideration of weathering, it is interesting to study the mass effect of the forces. This may be done by comparing the chemical analysis of a clay with that of the unweathered rock mass beneath. The assumption must be accepted, of course, that the rock analyzed is of the same composition as that from which the soil material was derived. The data are in terms of percentage.

FRESH GRANITE AND ITS RESIDUAL CLAY[a]

Constituents	*Rock*	*Clay*	*Percentage Lost*
SiO_2	60.69	45.31	52.45
Al_2O_3	16.89	26.55	0.00
Fe_2O_3	9.06	12.18	14.35
CaO	4.44	0.00	100.00
MgO	1.06	0.40	74.70
K_2O	4.25	1.10	83.52
Na_2O	2.82	0.22	95.03
P_2O_5	0.25	0.47	0.00
Ignition	0.62	13.75	gain

VIRGINIA LIMESTONE AND ITS RESIDUAL CLAY[b]

Constituents	*Rock*	*Clay*	*Percentage Lost*[c]
SiO_2	7.41	57.57	27.30
Al_2O_3	1.91	20.44	0.00
Fe_2O_3	0.98	7.93	24.89
CaO	28.29	0.15	99.83
MgO	18.17	1.21	99.38
K_2O	1.08	4.91	57.49
Na_2O	0.09	0.23	76.04
P_2O_5	0.03	0.10	68.78
CO_2	41.57	0.38	99.15
H_2O	0.57	6.69	gain

[a] Merrill, G. P., "Weathering of Micaceous Gneiss," *Bulletin Geol. Soc. Amer.*, 8: 160, 1879.

[b] Diller, J. S., "Educational Series of Rock Specimens," *Bulletin 150, U. S. Geol. Survey*, p. 385, 1898.

[c] It is to be noted that the "Percentage Lost" figures are comparative rather than absolute. This is because alumina is considered to have suffered no loss, which is not, as we now know, a tenable assumption.

various horizons of soil profiles is due, it must always be remembered, to the differential action of the same chemical forces that have developed the parent materials.

11:4. WEATHERING IN ACTION—GENESIS OF PARENT MATERIALS

An understanding, even though it may be limited, of the influences of the separate forces of weathering makes it possible to picture in a simple way the development of parent material from bedrock. A physical weakening, due usually to temperature changes, initiates the process, but it is accompanied and supplemented by certain chemical transformations. Such minerals as the feldspars, mica, horneblende, and the like suffer hydrolysis and hydration, while part of the combined iron is oxidized and hydrated. The minerals soften, lose their luster, and increase in volume. If hematite or limonite is formed, the decomposing mass becomes definitely red or yellow. Otherwise, the colors are subdued.

Coincident with these changes, such active cations as calcium, magnesium, sodium, and potassium suffer carbonation and solution. Then as the water present drains away, these constituents are removed, leaving a residue more or less bereft of its easily soluble bases. As the process goes on, all but the most resistant of the original minerals disappear, and their places are occupied by secondary hydrated silicates that tend to recrystallize into highly colloidal clay (page 90). When this clay is small in amount, a sandy soil material is developed, but when clay dominates, the mass is likely to be heavy and plastic.

Such a brief statement of rock weathering demands certain supplementary explanations. In the first place, it must be recognized that the intensity of the various agencies will fluctuate with climate. Under arid conditions, the physical forces will tend to dominate, and the resultant soil material will be coarse. Temperature changes, wind action, and water erosion will be accompanied by a minimum of chemical action.

In a humid region, however, the forces are more varied, and practically the full quota will be energetically at work. Vigorous chemical changes will accompany disintegration, and the result will be shown in the greater fineness of the product. Clayey materials will be more evident, and a higher colloidality can be expected. Moreover, the process is more likely to be hastened and intensified by decaying organic matter.

It must be remembered that the forces of weathering lose their in-

tensity as one goes downward from the surface. Also, the transformations, both physical and chemical, are in general somewhat different. The loss in intensity is to be expected as the upper layers of the debris protect those below. The differences in the nature of the weathering are not so easily accounted for. Undoubtedly, the lack of organic matter is a factor as well as the decrease in the porosity and aeration of the under-layers. This differentiation with depth is the forerunner of a profile development if and when soil genesis takes place.

It is well to remark also that the parent material, developing as described, may be subject to considerable transportation. Thus, new forces are brought to bear, initial processes are intensified or retarded, and the whole course of the weathering may be greatly modified. Glacial debris, alluvium, and windblown materials are common examples of such mass transfers.

11:5. COLORATION DUE TO WEATHERING

The presence of iron, as already noted, is a very important factor in rock weathering, and the discoloration due to its hydration and oxidation is an unfailing indication of chemical decay. The iron in decomposing minerals usually emerges as the ferrous oxide (page 301) and, as such, is soluble, especially if the circulating waters carry carbon dioxide. Under such conditions, oxidation goes on rapidly, and the iron passes to the ferric state and probably is first deposited as a relatively insoluble hydrated oxide—limonite or one of the other members of this indefinite group.[6] The yellow coloration so common on weathered minerals is an indication of this. Later, sufficient dehydration may occur to develop hematite and its various shades of red.

The high temperatures in the tropics and semi-tropics and in the warmer portions of temperate regions encourage the development of such intense red and yellow colors as to excite frequent comment. The parent materials of the Piedmont Plateau and the Appalachian valleys in the United States

[6] The compositions of hematite and of the limonite group indicate the possibility of a progressive change from red to yellow by hydration. The formulae for the various limonite compounds are more or less conjectural.

Hematite		Fe_2O_3	Red ↑
Limonite group	Turgite	$2\ Fe_2O_3 \cdot H_2O$	
	Geothite	$Fe_2O_3\ H_2O$	
	Limonite	$2\ Fe_2O_3 \cdot 3\ H_2O$	
	Xanthosiderite	$Fe_2O_3 \cdot 2\ H_2O$	
	Limnite	$Fe_2O_3 \cdot 3\ H_2O$	↓ Yellow

and the red earths of the Mediterranean regions, of Central America, and of Hawaii are examples. Even recently weathered products in the north temperate regions may show distinct yellowish colorations or tinges of pink or red.

Not all parent materials, however, have acquired their color as a result of the weathering of bed rock. With materials from red sandstones and shales, the oxidation of the iron has, of course, occurred before or as the rocks were formed. Here is a color carry-over of millions of years—an inherited characteristic. In the United States the colors of the Grand Canyon, Zion National Park, and Bryces Canyon are good examples of this.

11:6. GEOLOGIC CLASSIFICATION OF PARENT MATERIALS

In discussing weathering, it was tacitly assumed that parent material could originate in a number of different ways. In addition, it was suggested that this unconsolidated debris might lie in its original position above bed-rock for centuries or it might sooner or later be moved to new positions by the mechanical forces of nature.

On this basis, two groups of inorganic parent materials, designated as *sedentary* and *transported,* are usually recognized. The latter may be subdivided according to the agencies of transportation and deposition as follows:

1. Sedentary—still at original site		Residual
2. Transported—	Gravity	Colluvial
	Water	Alluvial Marine Lacustrine
	Ice	Glacial
	Wind	Aeolian

While these terms relate only to the placement of the parent materials, it has become customary to use them loosely in referring to the soils that have been developed by the weathering of these deposits. Hence, much is heard of *glacial* soils, *alluvial* soils, *residual* soils, and the like. Such a grouping is very general, however, as a wide diversity is sure to occur within each soil group so recognized. This renders the terms of little specific significance.

For example, the debris laid down by any particular agency is likely to be exceedingly variable. This variability will influence the resultant soils

for a very long time. Even under the same general climatic conditions, many kinds of soil may develop from practically identical parent material because of differences in vegetative cover, slope, drainage, depth, and organic accumulation. Again, differences in climate tend to produce, after long periods, soil profiles of great diversity, despite the original similarity of the soil materials. Hence, the classification cited is of value only in a broad geologic way and therefore should not be used in the characterization of soils except in a most generalized sense.

11:7. RESIDUAL PARENT MATERIAL

This type of regolith develops in place from the country rock below and has suffered little transportation. Much knowledge of weathering has been obtained by comparing the composition of such debris with that of the bedrock providing the latter is the same as that from which the parent material had its origin. (See note, page 302.)

Residual material, if typically developed, has usually suffered long and often intense weathering. If occurring in a warm humid climate, it is likely to be thoroughly oxidized and well leached. Even though it may come from rocks such as limestone, it is often comparatively low in calcium due to the ready loss of this constituent. Red and yellow colors are characteristic when weathering has been intense, as may be demonstrated by a trip through the Piedmont Plateau of eastern United States. In cooler, and especially in drier climates, residual weathering is much less drastic, and the oxidation and hydration of the iron may be hardly noticeable. Also, the lime content is higher and the colors of the debris subdued. Tremendous areas of this type of debris are found on the Great Plains and in other regions of western United States.

Residual materials are of wide distribution on all of the continents. In the United States, a glance at the physiographic map (Fig. 11:1) shows six great eastern and central provinces—the Piedmont Plateau, Appalachian Mountains and plateaus, the limestone valleys and ridges, the limestone and sandstone uplands, and the Great Plains region. The first three groups alone encompass about 10 per cent of the area of the United States. In addition, great expanses of sedentary accumulations are found west of the Rocky Mountains.

As might be expected, a great variety of soils occupy these regions covered by residual debris, since climate and vegetation, two of the determining factors in soil characterization, vary so radically over this great

area. It has already been emphasized that the profile of a mature soil is, at least in part, a reflection of ciimate and its accompanying vegetation.

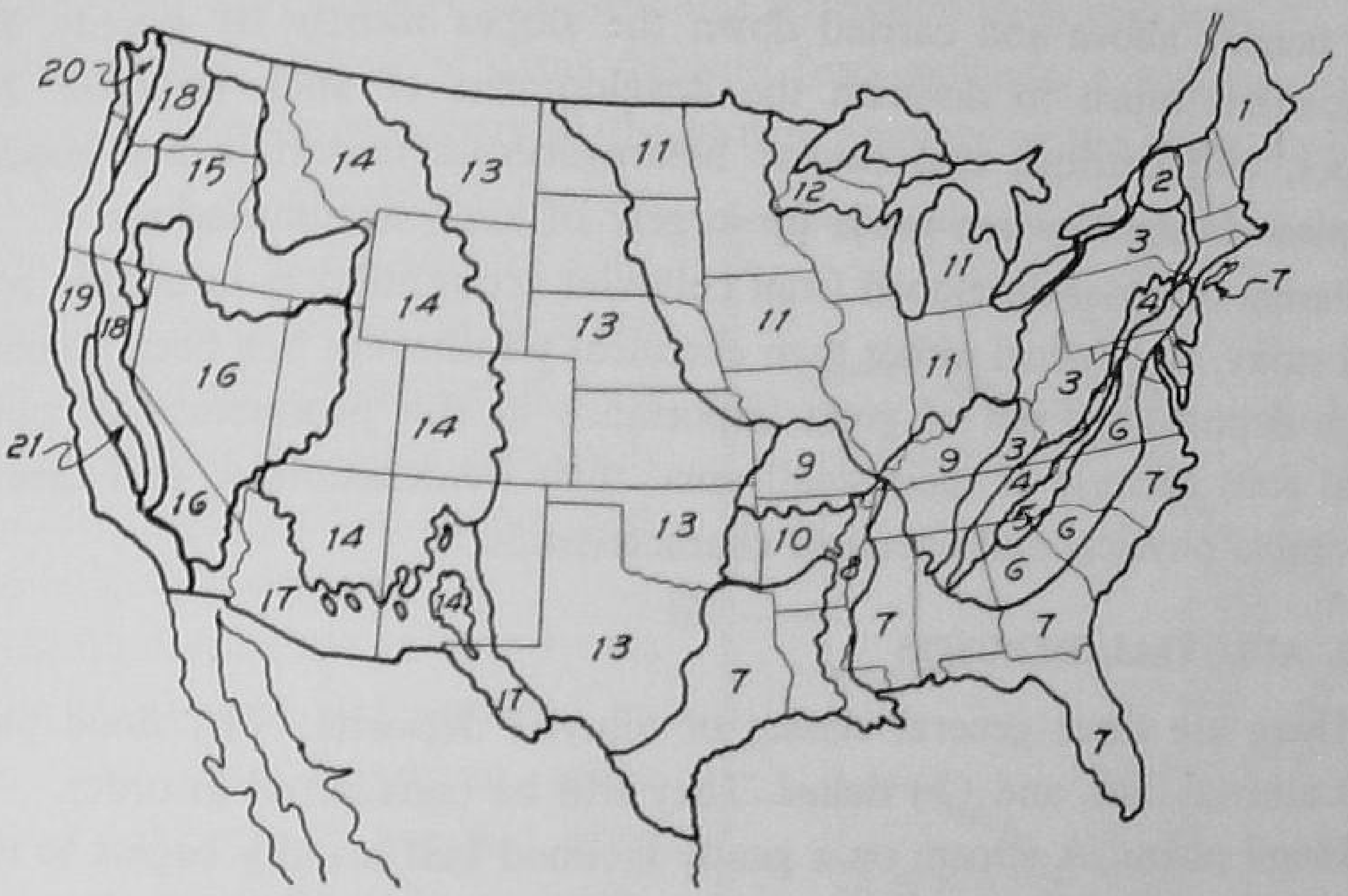

FIG. 11:1. *Generalized physiographic and regolith map of the United States. The regions located are as follows:*

1. *New England, mostly glaciated crystalline rocks.*
2. *Adirondacks, glaciated crystalline and sedimentary rocks.*
3. *Appalachian Mountains and Plateaus, shales and sandstones.*
4. *Limestone Valleys and Ridges, mostly limestone.*
5. *Blue Ridge Mountains, sandstones and shales.*
6. *Piedmont Plateau, crystalline rocks.*
7. *Atlantic Gulf and Coastal Plain, sands, clays, and limestones.*
8. *Mississippi Flood Plain and Delta, alluvium.*
9. *Limestone Uplands, mostly sandstone and shale.*
10. *Sandstone Uplands, mostly sandstone and shale.*
11. *Central Lowlands, mostly glaciated sedimentary rocks of many kinds. Great areas are overlaid with loess, a wind deposit of great agricultural importance (see Fig. 11:9).*
12. *Superior Uplands, glaciated crystalline and sedimentary.*
13. *Great Plains Region, sedimentary rocks of many kinds.*
14. *Rocky Mountain Region, mountains, uplands, and valleys.*
15. *Northwest Intermountain, mostly igneous crystalline rock. Great areas in Columbia and Snake Rivers basins are covered by loess (see Fig. 11:7).*
16. *Great Basin, gravels, sands, alluvial fans from various rocks.*
17. *Southwest Arid Region, gravel, sand and other debris of desert and mountain.*
18. *Sierra Nevada and Cascade Mountains, mountains, uplands, and valleys.*
19. *Pacific Coast Province, mountains and valleys, mostly sedimentary rocks.*
20. *Puget Sound Lowlands, glaciated sedimentary.*
21. *California central valley, alluvium and outwash.*

11:8. COLLUVIAL DEBRIS

Colluvial debris is made up of the fragments of rock detached from the heights above and carried down the slopes mostly by gravity. Frost action has much to do with the development of such deposits. Talus slopes, cliff detritus, and similar heterogeneous materials are good examples. Avalanches are made up largely of such accumulations.

Parent material developed from colluvial accumulation is usually coarse and stony, as physical rather than chemical weathering has been dominant. Such deposits are not of great importance in the production of agricultural soils because of their small area, their inaccessibility, and their unfavorable physical and chemical characteristics.

11:9. ALLUVIAL DEPOSITS

There are three general classes of alluvial deposits: (1) flood plains, (2) alluvial fans, and (3) deltas. They will be considered in order.

Flood plains. A stream on a gently inclined bed usually begins to swing from side to side in variable curves, depositing alluvial material on the inside of the curves and cutting on the opposite banks. This results in oxbows and lagoons, which are ideal for the further deposition of alluvial matter and the development of swamps. This state of meander naturally increases the probability of overflow at high water, a time when the stream is carrying much suspended matter. Part of this sediment is deposited over the flooded areas; the coarser near the channel, building up natural levees; the finer farther away in the lagoons and slack water. Thus, there are two distinct types of first-bottom deposits—*meander* and *flood*. As might be expected, flood-plain deposits are variable, ranging texturally from gravel and sands to silt and clay.

Due to a change in grade, a stream may cut down through its already well-formed alluvial deposits, leaving *terraces* on one or both sides. Often two, or even three, terraces of different heights may be detected along some valleys, marking a time when the stream was at these elevations. Terraces are especially characteristic of streams in or near glaciated regions, the valley fill having taken place during the waning stages of the ice age. Such deposits, however, are usually classified as glacial outwash rather than true alluvium.

Flood-plain deposits are found to a certain extent beside every stream, the greatest development in the United States occurring along the Missis-

sippi. (See Fig. 11:2.) This area varies from 20 to 75 miles in width and has a length from Cairo, Illinois to the Gulf of over 500 miles. The soils derived from such sediments usually are very rich, but if they are first bottoms, they may require drainage and protection from overflow.

Alluvial fans. Where streams descend from uplands, a sudden change in gradient sometimes occurs as the stream emerges at the lower level. A deposition of sediment is thereby forced, giving rise to *alluvial fans.* They differ from deltas in their location and in the character of their debris. Fan material often is gravelly and stony, more or less porous and, in general, well drained.

Alluvial fan debris is found over wide areas in arid and semiarid regions. The soils therefrom, when irrigated and properly handled, often prove very productive. Even in humid regions, such deposits, especially in certain glaciated sections, occur at times in large enough areas to be of considerable agricultural importance.

FIG. 11:2. *The flood plain and delta of the lower Mississippi River. This is the largest continuous area of alluvial soil in the United States.*

Delta deposits. Much of the finer sediment carried by streams is not deposited in the flood plain but is discharged into the body of water to which the stream is tributary. Unless there is sufficient current and wave action, the suspended material, in part, accumulates, forming a delta. Such delta deposits are by no means universal, being found at the mouths of only a small proportion of the rivers of the world. A delta often is a continuation of a flood plain, its front so to speak, and is not only clayey in nature but is likely to be swampy as well. The deltas of the Nile and the Po are good examples of this set of conditions.

Delta sediments, where they occur in any considerable acreage and are

subject to flood control and drainage, become rather important agriculturally. The combination deltas and flood plains of the Mississippi, Ganges, Po, Tigris, and Euphrates rivers are striking examples. Egypt, for centuries the granary of Rome, bespeaks the fertility and productivity of soils originating from such parent material.

11:10. MARINE SEDIMENTS

Much of the sediment carried away by stream action is eventually deposited in the oceans, seas, and gulfs, the coarser fragments near the shore, the finer particles at a distance. Also, considerable debris is wrenched from the shore line by the pounding of the waves and the undertow of the tides. If there have been changes in shore line, the alternation of beds will show no regular sequence and considerable variation in topography, depth, and texture. These deposits have been extensively raised above sea level along the Atlantic and Gulf coasts of the United States and elsewhere, and have given origin to large areas of valuable soils. (See Fig. 11:3.)

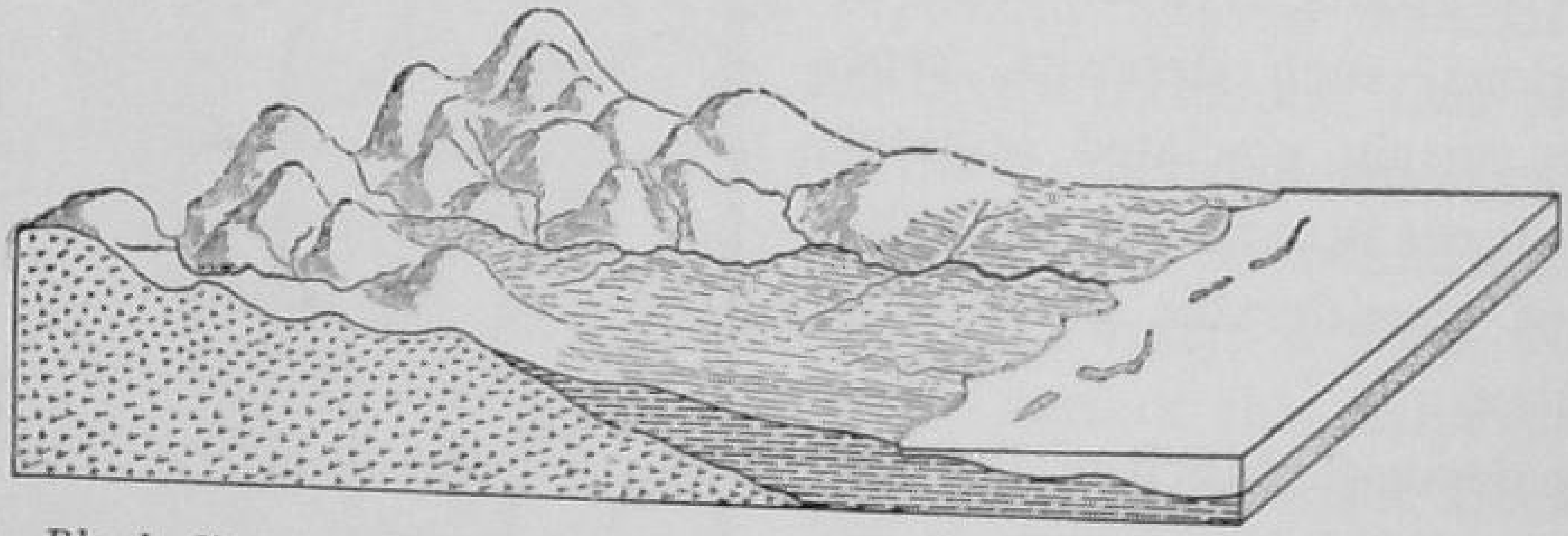

FIG. 11:3. *Block diagram showing the location of marine sediments and their relation to the uplands. The emerged coastal plain has already suffered some dissection from stream action.*

Marine deposits have been worn and triturated by a number of agencies. First, the weathering and erosion necessary to throw them into stream suspension were sustained. These were followed by the sorting and solvent action of the stream itself. Next, the sediment was swept into the ocean to be deposited and stratified, possibly after being pounded and eroded by the waves for years. At last came the emergence above the sea and the final action of the forces of weathering. The latter effects are of great moment, since they determine the topography and, to a considerable extent, the chemical and physical nature of the resultant parent material.

The marine sediments of the United States, although they have been

subjected to weathering a shorter time than some of the residual debris, are generally more worn and usually carry less of the mineral nutrient elements. Their silica content is high, and they are often sandy, especially along the Atlantic seaboard. But in the Atlantic and Gulf coastal flatwoods and the interior pine lands of Alabama and Mississippi, clayey deposits are not uncommon. It is interesting to note that these marine clays may be dominated by kaolinite, illite, or montmorillonite.

In continental United States, the marine deposits of the Atlantic and Gulf coastal provinces (see Fig. 11:1) occupy approximately 11 per cent of the country and are very diversified due to source of material, age, and the climatic conditions under which they now exist. Severe leaching as well as serious erosion occurs in times of heavy rainfall. In spite of this, however, their soils support a great variety of crops when adequately supplied with organic matter, properly cultivated and carefully fertilized.

11:11. THE PLEISTOCENE ICE AGE

During the Pleistocene,[7] northern North America as well as northern and central Europe and parts of northern Asia were invaded by a succession of great ice sheets. Certain parts of South America as well as areas in New Zealand and Australia were similarly affected. And Antarctica undoubtedly was capped with ice much as it is today.[8] The cause was a change in temperature and precipitation accompanied by other fluctuations. But just why the climatic changes occurred is highly conjectural.

This change in climate that permitted the onset of the Pleistocene ice age evidently brought a lowering of temperature and an increase in precipitation. During this period the heat of summer did not by any means melt the winter accumulations of snow. Hence, great snow fields formed at certain centers. As the snow continued to thicken, the increasing pressure

[7] For supplementary reading as to the Great Ice Age and its influence, see:
Daly, R. A., *The Changing World of the Ice Age,* Yale University Press, New Haven, 1934.
Coleman, A. P., *The Last Million Years,* University of Toronto Press, Toronto, 1941.
Von Engeln, O. D., *Geomorphology,* The Macmillan Company, New York, 1942.
Flint, R. F., *Glacial Geology and the Pleistocene Epoch,* John Wiley and Sons, Inc., New York City, 1947.

[8] It is estimated that the Pleistocene ice at its maximum extension covered perhaps 20 per cent of the land area of the world. In this connection it is surprising to learn that present day glaciers, which we consider as mere remnants of the Great Ice Age, occupy almost half as much land surface. The respective amounts of ice, however, are not in the same proportion, since our living glaciers are comparatively thin and are definitely on the wane.

and the influence of summer melting gradually changed the snow into ice. Thus, great dome-shaped glaciers gradually came into being, incredibly thick in their region of accretion.[9]

In North America, the major centers of ice accumulation were in central Labrador and the western Hudson Bay region, with a minor concentration in the Canadian Rockies. From the major centers, great continental glaciers pushed outward in all directions but especially southward, covering, from time to time, most of what is now Canada and the northern part of the United States. The southernmost extension was down the Mississippi Valley, since here, due to the lower and smoother topography, the least resistance was met. (See Fig. 11:4.)

Central North America and Europe apparently sustained at least four[10] distinct ice invasions separated, in each case, by long interglacial periods. So long, in fact, were these ice-free intervals that they are estimated as having covered in total a period considerably longer than the time that ice actually blanketed the country.[11] The existence of these interglacial periods is conclusively proved by the presence of forest beds and accumu-

[9] At the Hudson Bay and Labradorian centers the ice perhaps attained a thickness of 2 or 3 miles. At present the average thickness of the mantle over Greenland is in the neighborhood of 3,000 feet with an estimated 9,000 feet at a maximum. The figures for Antarctica are known to be considerably greater, possibly double the depths suggested for Greenland. See Daly, R. A., *The Changing World of the Ice Age*, Yale University Press, New Haven, 1934.

It is estimated that so much water was changed to glacial ice that, at maximum glaciation, the ocean level was perhaps 250 feet lower than at present. The melting of our present day glaciers would raise the ocean level possibly as much as 50 feet.

[10] The ice invasions of central United States were recognized by early authorities as five in number: Nebraskan, Kansan, Illinoian, Iowan, and Wisconsin. At present, however, most glaciologists consider the Iowan and the various Wisconsin sheets as belonging to the same stage, thus giving a classification that correlates with that established for the glaciation of Europe. The loess covers parts of all of the American till sheets except the Wisconsin, the youngest. The glacial debris of eastern United States and Canada is practically all of Wisconsin age.

[11] The total length of the Pleistocene ice age as a minimum probably was in excess of 700,000 or even as long as 1,000,000 years. According to early estimates, the glacial ice disappeared from northern Iowa and central New York possibly only 25,000 to 30,000 years ago. More recent studies in the Middle West using radio-active carbon (C-14) indicate that these figures are too high. Perhaps 12,000 years is a more probable dating. We may be now enjoying the mildness of another interglacial period.

Of the three major interglacial periods, the first (Aftonian) persisted perhaps 200,000 years, the second (Yarmouth) may have lasted for 300,000 years, while the third (Sangamon), which preceded the Iowan and Wisconsin ice advance, possibly endured for 125,000 years. Assuming the Pleistocene age to have continued for not more than 1,000,000 years, it is obvious that glacial ice occupied what is now north central and northeastern United States less than half of the period designated as the Great Ice Age.

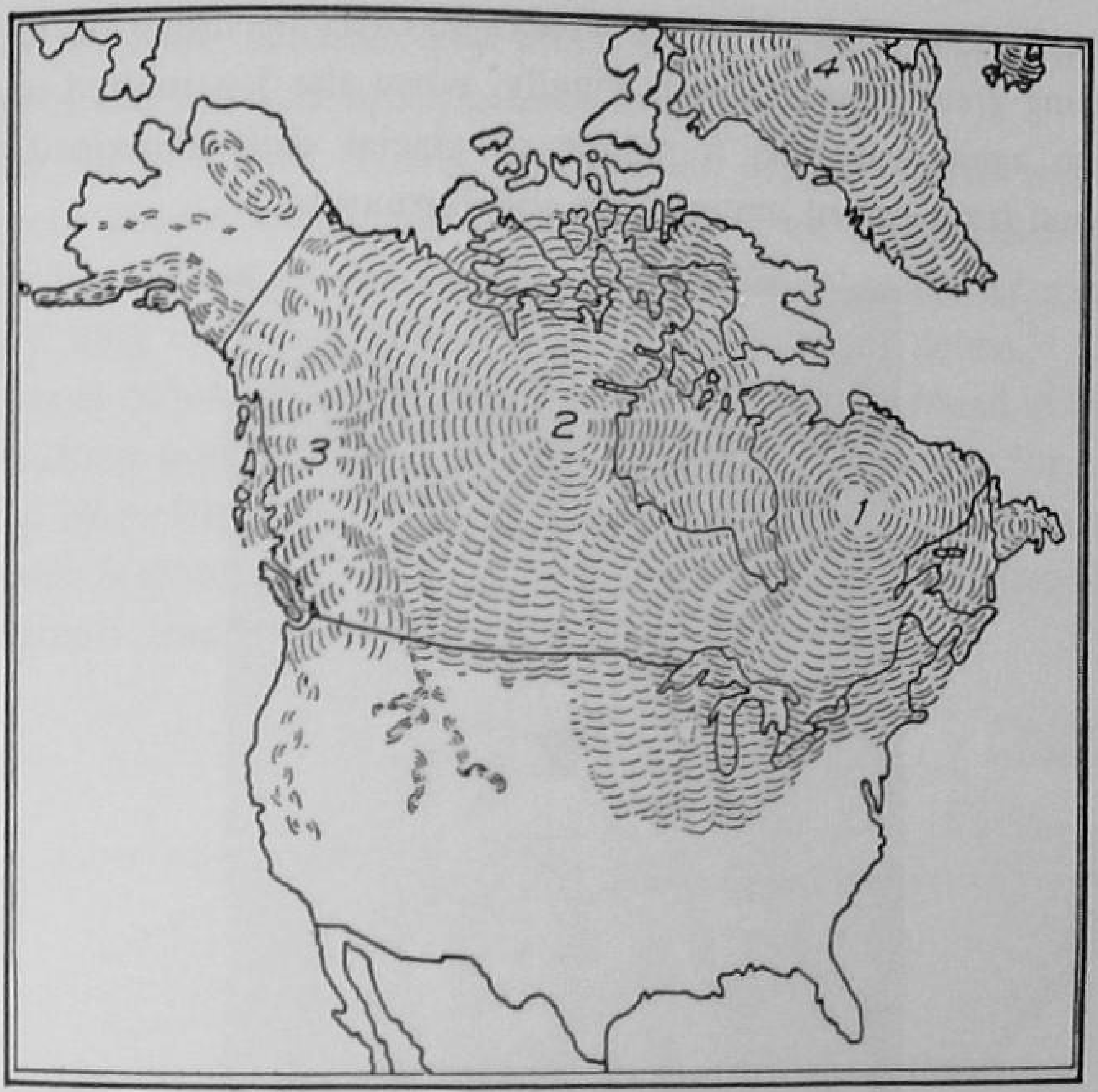

FIG. 11:4. *Sketch map of North America showing the maximum development of the continental glaciation. The three centers of ice accumulation are numbered. Apparently central and eastern United States were invaded from the Hudson Bay (2) and Labradorian (1) centers. Note the marked southernly advance of the ice in the Mississippi Valley where topography offered little resistance. To the eastward the Appalachian highlands more or less blocked the ice invasion.*

lations of peat between the glacial deposits of different ages and by evidence of the prolonged erosion of the successive layers of glacial drift. (See Fig. 11:5.) In certain places excavations yield clear evidence of fossil soils of mature age.[12] Some of the interglacial intervals evidently were times of warm or even semi-tropical climate in regions that are now definitely temperate.

As the glacial ice, coarsely crystalline and with a unique viscosity under this tremendous pressure, was pushed forward, it conformed itself to the unevenness of the areas invaded. It rose over hills and often over mountains with surprising ease. Not only was the existing regolith with its mantle of soil swept away, but hills were rounded, valleys filled, and, in some cases, the underlying rocks were severely ground and gouged. Thus,

[12] For examples, see: Simonson, R. W., "Studies of Buried Soils Formed from Till in Iowa," *Proc. Soil Sci. Soc. Amer.*, 6: 373–381, 1941.

raphy, color, texture, structure, depth, slope, and drainage. As might be expected, the soils derived from such soil material are most heterogeneous. Such variations serve to indicate that the term glacial soil is of value only in suggesting the mode in general of deposition of the parent materials. It indicates practically nothing as to the characteristics of a soil so designated.

11:13. GLACIAL OUTWASH AND LACUSTRINE SEDIMENTS

Great torrents of water were constantly gushing, especially during the summer, from the great Pleistocene ice sheets as their fronts advanced and retreated in response to their environment. The great loads of sediment carried by such streams were in part either dumped down immediately or carried to other areas for deposition. As long as the water had ready egress, it flowed rapidly away to deposit its load as outwash of various kinds.

Outwash plains. A type of deposit of great importance is the *outwash* plain, formed by streams heavily laden with glacial sediment. (See Fig. 11:6.) This sediment is usually assorted and therefore variable in texture. Such deposits are particularly important in valleys and on plains where the glacial waters were able to flow away freely. Such valley fills are common in the United States, both north and south of the terminal moraine. For example, extensive outwash plains occur on Long Island, New York, and on the eastern side of the great Central Valley of California. The latter is a glacial wash from the Sierra Nevadas. Even when such depositions are not of wide extent, their local importance is often very great. The small sand plains of New England are an instance of this as they offer ideal locations for villages and towns.

Glacial lake deposits. In many cases, however, the ice front came to a stand where there was no such ready escape for the water, and ponding due to the damming action of the ice occurred. (See Fig. 11:8.) Often, very large lakes were formed which existed for many years. Particularly prominent were those south of the Great Lakes in New York, Ohio, Indiana, Michigan, and in the Red River Valley. (See Fig. 11:7.) The latter lake, called Glacial Lake Agassiz, was perhaps 750 miles long and 250 miles wide at its maximum extension. The others, while individually much smaller, covered in total great stretches of country. Large lakes also occurred in the intermountain regions west of the rockies as well as in the Connecticut Valley in New England and elsewhere.

With the glacial ice melting rapidly in the hills and higher valleys, these

lakes were constantly fed by torrents from above which were laden with sediment derived not only directly from the ice but also from the unconsolidated till sheet over which they flowed. As a consequence, great

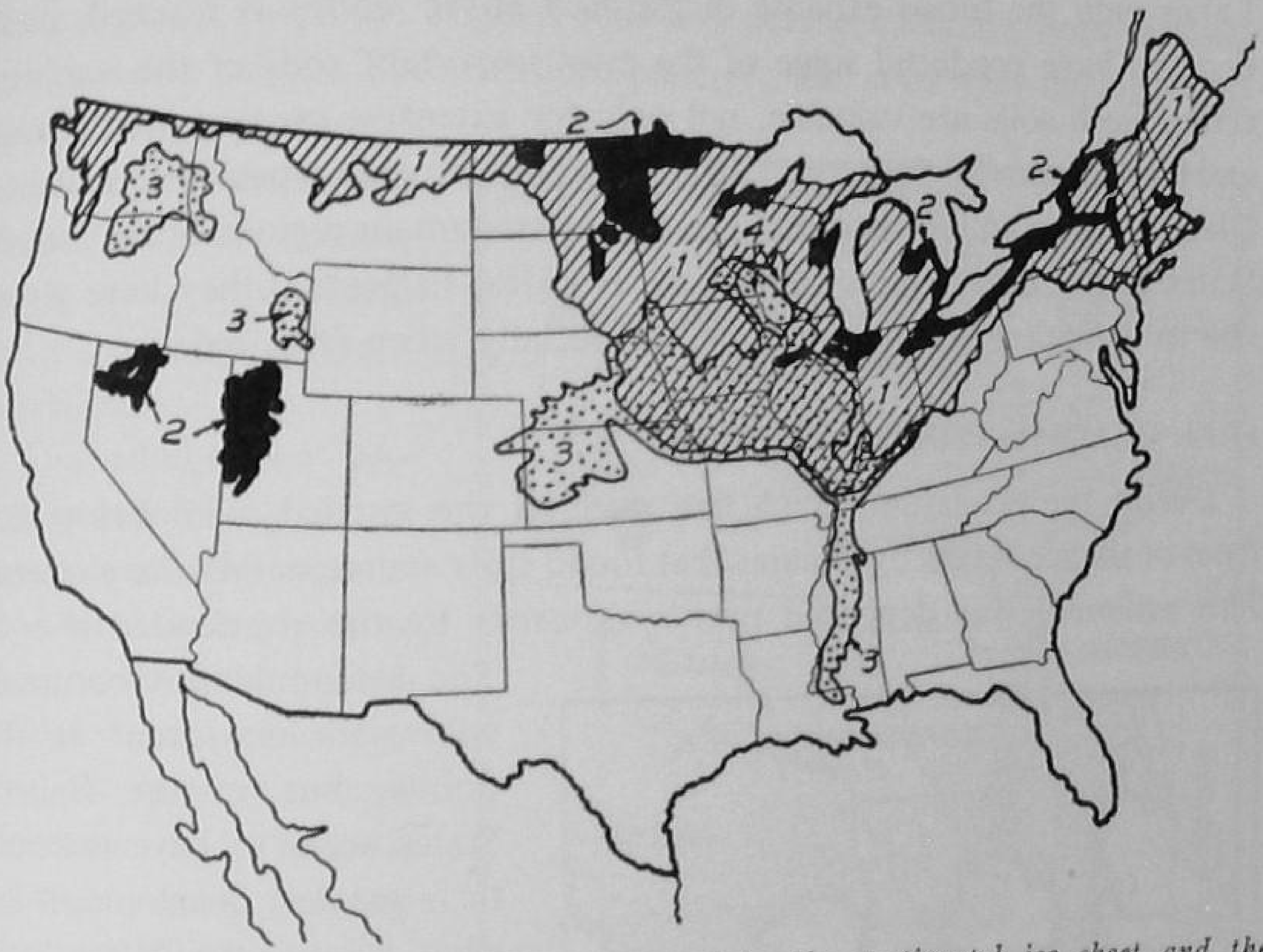

FIG. 11:7. *Areas in the United States covered by the continental ice sheet and the deposits either directly from, or associated with, the glacial ice. 1, till deposits of various kinds; 2, glacial-lacustrine deposits; 3, the loessial blanket—note that the loess overlies great areas of till in the Middle West; 4, an area, mostly in Wisconsin, that escaped glaciation. It is partially loess covered.*

deposits were made in these glacial lakes, ranging from coarse delta materials near the shore to fine silts and clay in the deeper and stiller waters. Such materials now cover large areas both in the United States and Canada, and their weathering has given rise to what are loosely designated as *glacial lake* soils. (See Fig. 11:7.)

Glacial lake deposits probably present as wide a variation in physical and chemical characteristics as the soil materials of any of the physiographic provinces. Being deposited by water, they have been subject to much sorting and stratification. They range from coarse gravels, on the one hand, to fine clays on the other. There is also considerable variation in respect to lime content, pH, color, and structural characteristics. They are generally found in the lowlands, although they may occur well up on the hillsides if the shores of the old lakes encroached this far.

The soils developed from these lake sediments are most heterogeneous. Weathering, due to climatic differences, has been variable, and profile contrasts are great. Extending westward from New England along the Great Lakes until the broad expanse of the Red River Valley is reached, these deposits have produced some of the most important soils of the northern states. Such soils are valuable, not only for extensive cropping with grain and hay but also for fruit, trucking, and other intensive types of agriculture. Glacial lake sediments also occur in the intermountain regions of the United States and at other places west of the Rockies. In general they have given rise to agriculturally important soils especially when irrigated.

11:14. GLACIAL-AEOLIAN DEPOSITS

During the glaciation, much fine material was carried miles below the front of the ice sheets by streams that found their source within the glaciers. This sediment was deposited over wide areas by the overloaded rivers. The accumulations occurred below the ice front at all points, but in the United States seem to have reached their greatest development in what is now the Mississippi and Missouri valleys. Some of the debris found on the Great Plains probably had a similar origin, coming from glaciers debouching from the Rockies. All this, added to the great stretches of unconsolidated till in the glaciated regions and the residual materials unclothed with vegetation on the great Plains, presented unusually favorable conditions for wind erosion in dry weather.

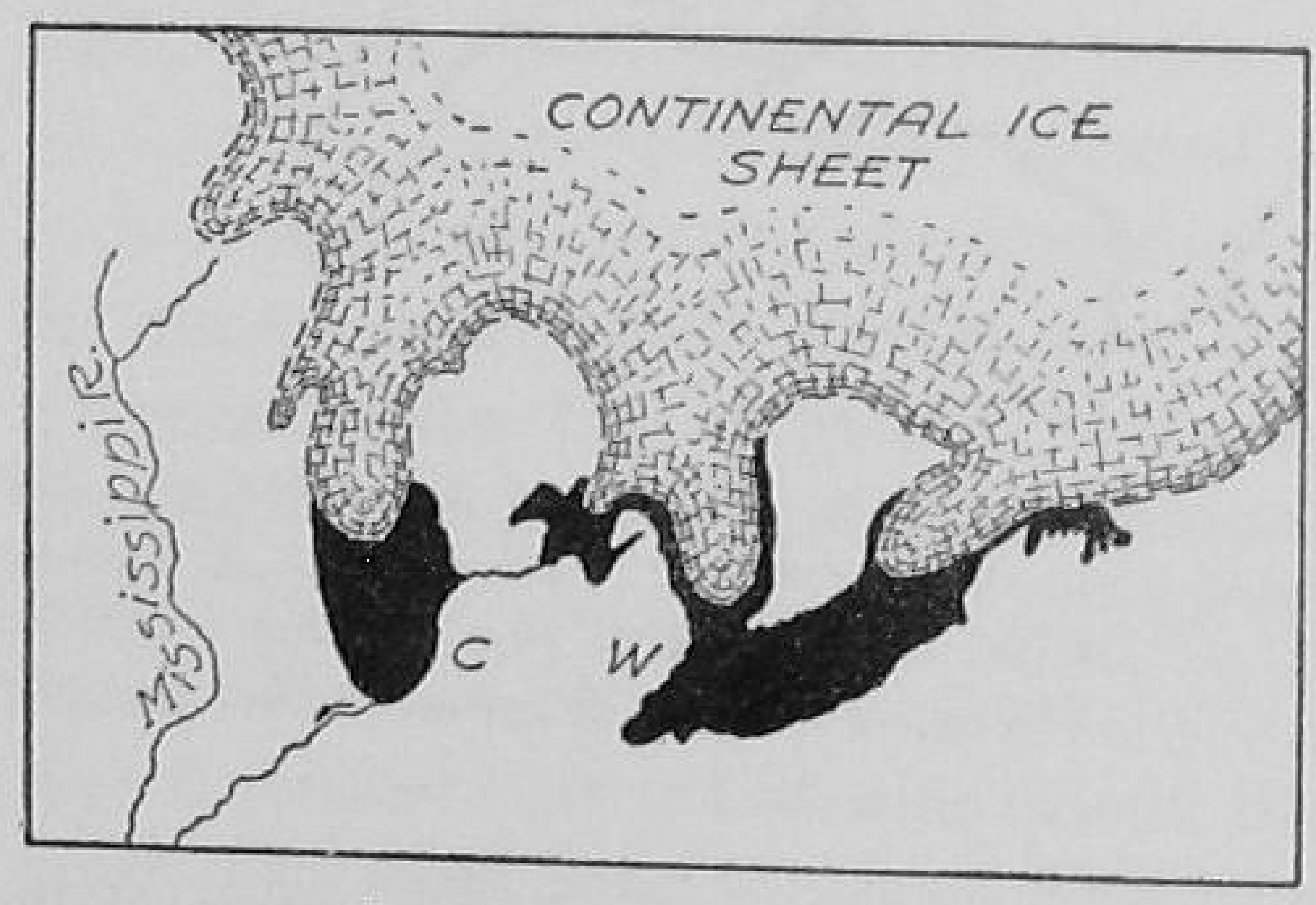

FIG. 11:8. *When conditions of topography were favorable, the Wisconsin ice sheet acted as a great waning dam. The diagram shows a stage in the development of glacial lakes Chicago and Warren. (After Daly.)*

Origin and location of loess. It is generally agreed by glaciologists that a period of aridity, at least as far as the Great Plains and contiguous eastward areas were concerned, accompanied or immediately followed the retreat of the Iowan sheet and perhaps extended well into the Iowan-Wisconsin interglacial interval. The low rainfall of this period was accompanied by strong westerly winds. These winds, active perhaps through

centuries, were instrumental in picking up and distributing fine material, both glacial and nonglacial in origin, over wide areas on the Great Plains and particularly in the Mississippi, Ohio, and Missouri valleys. These deposits cover the original soils and parent materials, both residual and glacial in origin. The situation, perhaps, was somewhat analogous to the wind erosion now experienced on the Great Plains but, of course, much more severe and under somewhat different conditions.

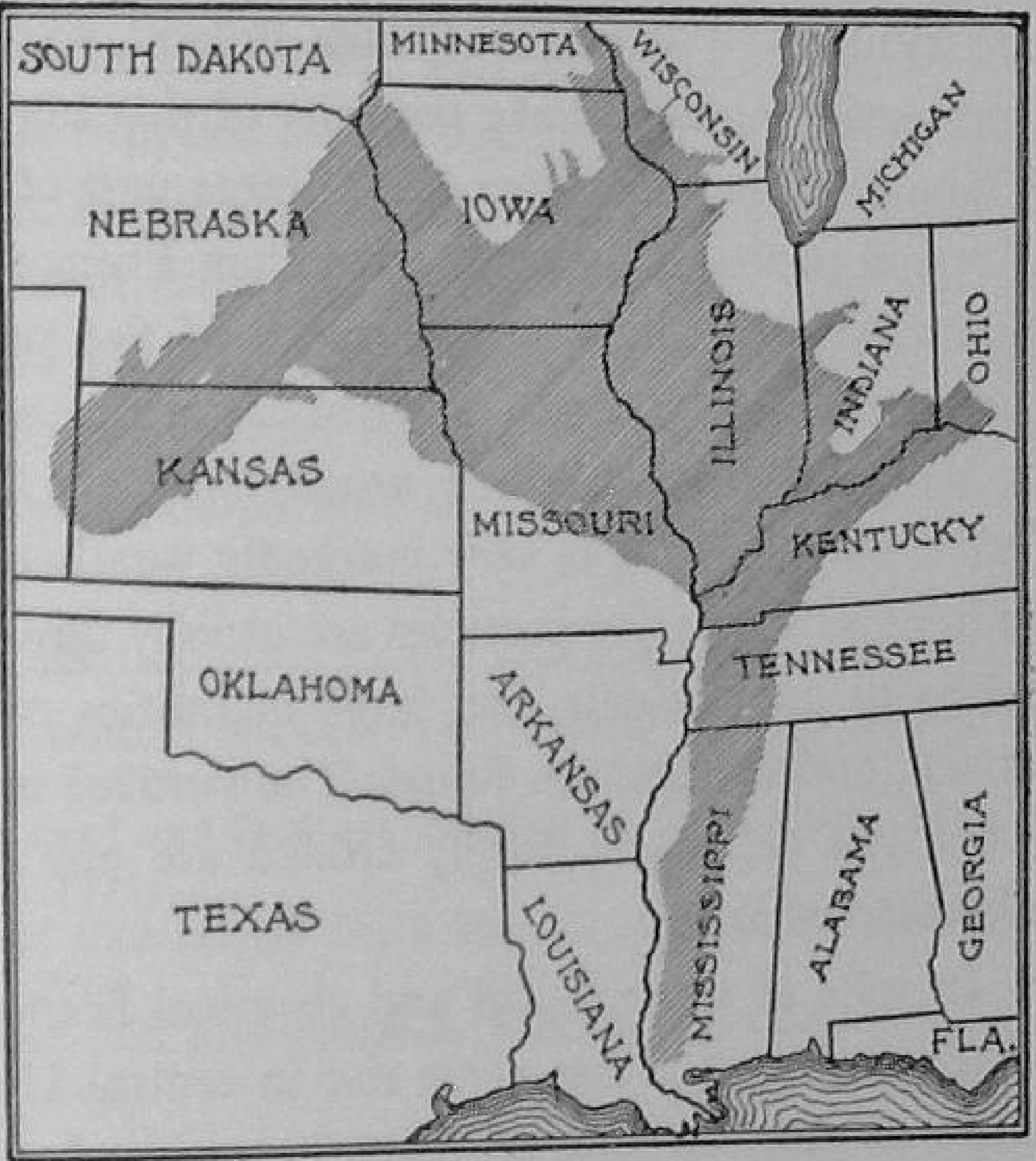

FIG. 11:9. *Approximate distribution of loess in central United States. The soil that has developed therefrom is generally a silt loam, often somewhat sandy. Note especially the extension down the eastern side of the Mississippi River and the irregularities of its northern extensions. Smaller areas of loess occur in Washington, Oregon, and Idaho. (See Fig. 11:7.)*

This wind-blown material, called *loess,*[14] is found over wide areas in the United States, in most cases masking the unconsolidated materials below. It covers eastern Nebraska and Kansas, southern and central Iowa and Illinois, northern Missouri, and parts of southern Ohio and Indiana, besides a wide band extending southward along the eastern border of the Mississippi River. (See Figs. 11:7 and 11:9.) Extensive loessial deposits also occur in the Palouse region in Washington and Idaho and other areas in northwestern United States. In places, notably along the Missouri and Mississippi rivers, its accumulation has given rise to great bluffs which bestow a characteristic topography to

[14] Aeolian deposits other than loess occur, such as adobe, volcanic ash, and sand dunes. *Adobe* is a term applied to a fine calcareous clay or silt formed in a manner somewhat like loess. It produces an exceedingly rich soil and is very productive when properly irrigated.

Soils from volcanic ash occur in Montana, Idaho, Nebraska, and Kansas. They are light and porous and not of great agricultural value. Sand dunes are of little value under any condition and become a menace to agriculture if they are moving.

the region. Farther from the rivers, the deposits, an upland type, are shallower and smoother in topography.

Not only is loess found over thousands of square miles in central and northwestern United States, but it occurs in certain other countries in large areas. It is greatly developed in northern France and Belgium and along the Rhine in Germany where it gives rise to important soils in the valleys that are tributary to that river. Silesia, Poland, southern Russia, Bohemia, Hungary and Roumania have deposits of this highly fertile parent material. In China, loess is found over a very large part of the valley of the Hwang Ho, a region probably larger in area than France and Germany combined. In South America, loess covers much of the pampa of northern Argentina, while considerable areas occur in eastern New Zealand.[15]

Nature of loess. Loess is usually silty in character and has a yellowish-buff color, unless it is very markedly weathered or carries a large amount of humus. The larger particles are usually unweathered and angular. Quartz seems to predominate, but large quantities of feldspar, mica, hornblende, augite, and the like are found. The vertical walls and escarpments formed when this deposit is deeply eroded are one of its most striking physical characteristics.

In spite of the physical and chemical homogeneity of the loess as originally deposited, it has given rise in central United States and elsewhere to soils of considerable diversity because of the climatic differences now existent in the various parts of the loessial area. A comparison of the loessial area of the Middle West (Fig. 11:9) with the map of the Great Soil Groups (Fig. 12:5) will show the presence of loess in six distinct soil regions. This situation, while indicating the probability of great differences in the fertility and productivity of loess soils, especially emphasizes the influence of climate as the final determinate of soil characteristics.[16]

[15] All of the loessial deposits mentioned apparently are related directly or indirectly to glaciation except that of China. Here the debris originated as residual material in the arid regions to the northwest and, in some places, is still noticeably in motion.

[16] A great deal has been written about loess and loessial soils. Here are a few recent articles dealing with the soils of the Mississippi Valley of loessial origin.

Vanderford, H. B., and W. A. Albrecht, *The Development of Loessial Soils in Central United States as It Reflects Differences in Climate,* Research Bulletin 345, Missouri Agr. Exp. Sta., 1942.

Smith, Guy D., *Illinois Loess,* Bulletin 490, Illinois Agr. Exp. Sta., 1942.

Hutton, C. E., "Studies of Loess-Derived Soils of Southwestern Iowa," *Proc. Soil Sci. Soc. Amer.,* 12: 424–431, 1947.

Wascher, H. L., R. P. Humbert, and J. G. Cady, "Loess in the Southern Mississippi: Identification and Distribution of the Loess Sheet," *Proc. Soil Sci. Soc. Amer.,* 12: 389–399, 1947.

11:15. THE AGRICULTURAL SIGNIFICANCE OF THE GLACIATION

The Pleistocene glaciation, in most cases, has been a decided benefit, especially agriculturally. The leveling and filling actions, when drift was abundant, have given a smoother topography more suited to farming operations. The same can be said for the glacial lake sediments and loess deposits. Also, the parent materials thus supplied are geologically fresh, and the soils derived therefrom usually are, in general, not drastically leached. While it is difficult to show any consistent difference in total nutrients between the old residual and the younger glacial soils, it is generally admitted that glaciation has been a benefit to agriculture. Young soils generally are higher in available nutrients, and under comparable conditions they are superior in crop-producing power.[17]

Beavers, A. H., and W. A. Albrecht, "Composition of Alluvial Deposits Viewed as Probable Sources of Loess," *Proc. Soil Sci. Soc. Amer.*, 13: 468–470, 1948.

[17] Whitbeck, R. H., "The Glaciated and Driftless Portions of Wisconsin," *Bulletin, Geog. Soc. Phil.*, 9, No. 3: 10–20, 1911.

Von Engeln, O. D., "Effects of Continental Glaciation on Agriculture," *Bulletin, Geog. Soc. Amer.*, 46: 353–355, 1914.

Ames, J. W., and E. W. Gaither, *Soil Investigations*, Bulletin 261, Ohio Agr. Exp. Sta., 1913.

CHAPTER

12

Soil Formation, Classification and Survey

TO STUDY satisfactorily any heterogeneous group in nature some sort of classification is necessary. This is especially true of soils. The value of experimental work of any kind is seriously restricted and may even be misleading unless the relation of one soil to another is known. Knowledge of crop requirements in any region is of uncertain value without some understanding of the formative processes of the soils in question and of their present profile similarities and differences.

In arriving at such an understanding three phases must be considered: (1) soil genesis or the evolution of a soil from its parent material, (2) soil classification, in this case especially as it applies to the United States, and (3) soil survey, its interpretation and utilization. It will be observed, as the viewpoint is amplified, that these phases are progressively interlocked, and that this sequence is fundamental to the satisfactory understanding and study of soils as they occur in the field.

12:1. WEATHERING AND SOIL FORMATION

To every thinking person it is obvious that mineral soils have originated from the unconsolidated materials that mask the country rock. This mantle of materials, the *regolith,* has in turn been differentiated from solid rock by the same agencies. The general trend of events as bedrock is disintegrated and in part decomposed to give parent material has already been sketched (page 303).

Even a superficial examination will show that the weathering process seems in a broad way to be destructive. Thus, minerals present in the original unweathered rocks are continually subject to decomposition and dis-

integration. As weathering proceeds soluble constituents are lost in the drainage waters, leaving secondary minerals such as *iron oxide* and *silicate clays* as products of seemingly destructive processes.

At this point a very pertinent question logically arises. How can the soil, a natural body resulting in part, at least, from synthesis, be developed by forces that are recognized the world over as wasteful and destructive? Why do not the original changes continue until the upper layer of the regolith is reduced to an inert mass, more or less free of soluble constituents, and hence incapable of supporting plant life?

Synthesis of clay and humus the answer. In the first place the disruption of the original silicate minerals paves the way for clay formation. The genesis of clay has already been discussed (page 90) and its importance in relation to soil fertility fully emphasized. In fact, the natural fertility of mineral soils cannot be high without this particular synthesized product of weathering.

But this is by no means all. At very early stages of soil formation living organisms decisively intervene. Organic matter accumulates, especially at the surface, and the whole trend of the weathering is sharply modified. It now becomes *bio*chemical and *bio*colloidal. Colloidal humus supplements colloidal clay as a retainer of nutrients. Physically, particularly as regards structure, the soil mass becomes modified as a result of biotic influences.

Perhaps of even greater import is the fact that higher plants partially reverse the over-all downward movement of soluble constituents. Mineral elements are brought to the surface and deposited as part of organic residues. This retards their loss from the soil and encourages further biological activity. The accumulation and activity of organic matter, both living and dead, therefore, is the real secret, together with clay synthesis, of what may be termed *constructive* weathering.

Thus weathering, a *producer* of parent materials, and weathering, a *builder* of soils, operate simultaneously. Fundamentally the same processes are involved in both cases. These processes result in the destruction or alteration of parent materials and at the same time give rise to products which are essential for soil formation. Ultimately, therefore, the physical and biochemical forces are acting on a mixture of substances differing markedly from the parent material. Moreover, these weathering influences give rise to a horizontal layering within the soil mass and a *profile*, which is both characteristic and unique, is developed. As this differentiation progresses, a new natural body—a soil—comes into being.

12:2. DEVELOPMENT OF SOIL CHARACTERISTICS—SOIL AGE

When soil formation begins, the characteristics of the weathering mass are almost entirely those of the parent material. These characteristics are lithological or *inherited*. As yet there has been no profile development in a soil sense. Any layering that may be evident is geological, that is, related to the deposition of the regolith. Sands and recent alluvium are good present-day examples.

As the influence of weathering becomes constructive in a soil sense and the presence of organic matter begins to exert its influence, a *young soil* gradually develops. Acquired [1] characteristics, that is, those induced largely by the environment, are noticeable but those inherited from the parent material are still dominant. The profile is only faintly developed, however, since the constructive agencies have not had time to impress their pattern.

However, as the environmental factors gradually attain the ascendancy, the new or acquired characteristics become dominant and the profile is much more fully developed. Inherited characteristics, although still in evidence, are definitely of minor importance in determining soil properties. The soil is now said to be *mature*. In other words, it has reached *dynamic equilibrium* with its particular environment.

This by no means indicates that soil forming processes do not continue to operate. On the contrary, they may be at the peak of their intensity when the soil reaches maturity. The over-all effect, however, is one which leaves the essential profile characteristics largely unchanged. Normal erosion at the surface and inclusions from the C horizon below tend to balance each other and thereby aid in maintaining these characteristics.

A relatively constant climatic environment is assumed when we speak of mature soils. As would be expected, however, changes in the environment do occur and these changes alter the characteristics of even mature

[1] Examples of *inherited* and *acquired* characteristics are quite numerous. The presence of quartz is perhaps the most common example of the former, although the presence of any mineral, such as feldspar or mica, carried over unchanged into a soil, is a good illustration. Color also is often inherited, as in the case of a red parent sandstone or shale. Even clay, if originally a part of the parent material, may be rated as lithological.

Examples of *acquired* characteristics are as easily cited. Those due to organic matter, to clay formed as the soil developed, and to products of weathering such as red and yellow iron oxides are common. Certainly profile layering and the development of various structural forms within the various horizons are due largely to environmental influences. Acquired characteristics of a more local nature, such as imperfect drainage and the accumulation of alkali salts, should also be mentioned.

soils. Under these conditions the soil that results is said to be *degraded.* The encroachment of a forest on a prairie is a good example, some of the characteristics induced by grass yielding to those of a wooded environment.

In the sequence of events described above it should be emphasized that *soil age* and *the length of time necessary for soil development* are not synonymous. Two soils may have been subjected to weathering forces for the same length of time and yet may *not* be of the same age. For example, the presence of $CaCO_3$ in the parent material will delay the maturing of a soil if its maturation is dependent upon leaching of bases. Thus, a soil developing from sandstone in such a climatic environment would reach maturity much more quickly than one developing from limestone. The real criterion of soil maturity is, therefore, not the weathering time, but rather the development and stabilization of a characteristic soil profile.

Briefly then, a *young* soil is one that is still in the process of adjustment to its environment. A *mature* soil, on the other hand, is in dynamic equilibrium with climatic and vegetative influences, and the profile horizons are not appreciably changing either physically or chemically. We are now ready to consider the nature of the profile that a well-drained mature soil is likely to present.

12:3. THE SOIL PROFILE

As parent material is molded into a soil by the biochemical means described above, a more or less definite layering develops, especially if drainage is adequate. This zoning is particularly noticeable near the soil surface. Here, climatic agencies are more intense and there has been an opportunity for the accumulation of organic matter. A section down through the various layers to, or into, the less weathered parent material is the *profile* already so frequently mentioned. The texture, depth, color, chemical nature, and sequence of the various horizons characterize a soil and determine its agricultural value. Profile study is, therefore, of prime importance. (See page 4.)

Soil horizons. For convenience in study and description, the layers resulting from soil forming processes are grouped under three heads: A, B, and C. (See Fig. 12:1.) The subdivisions of these are called *horizons.* The A group (eluvial) [2] lies at the surface and is characterized as a zone of maximum leaching. Beginning at the surface of the mineral matter the horizons are designated as A_1, A_2, etc. If a layer of organic matter covers

[2] Eluvial from *ex* or *e* meaning out and *luv,* washed.

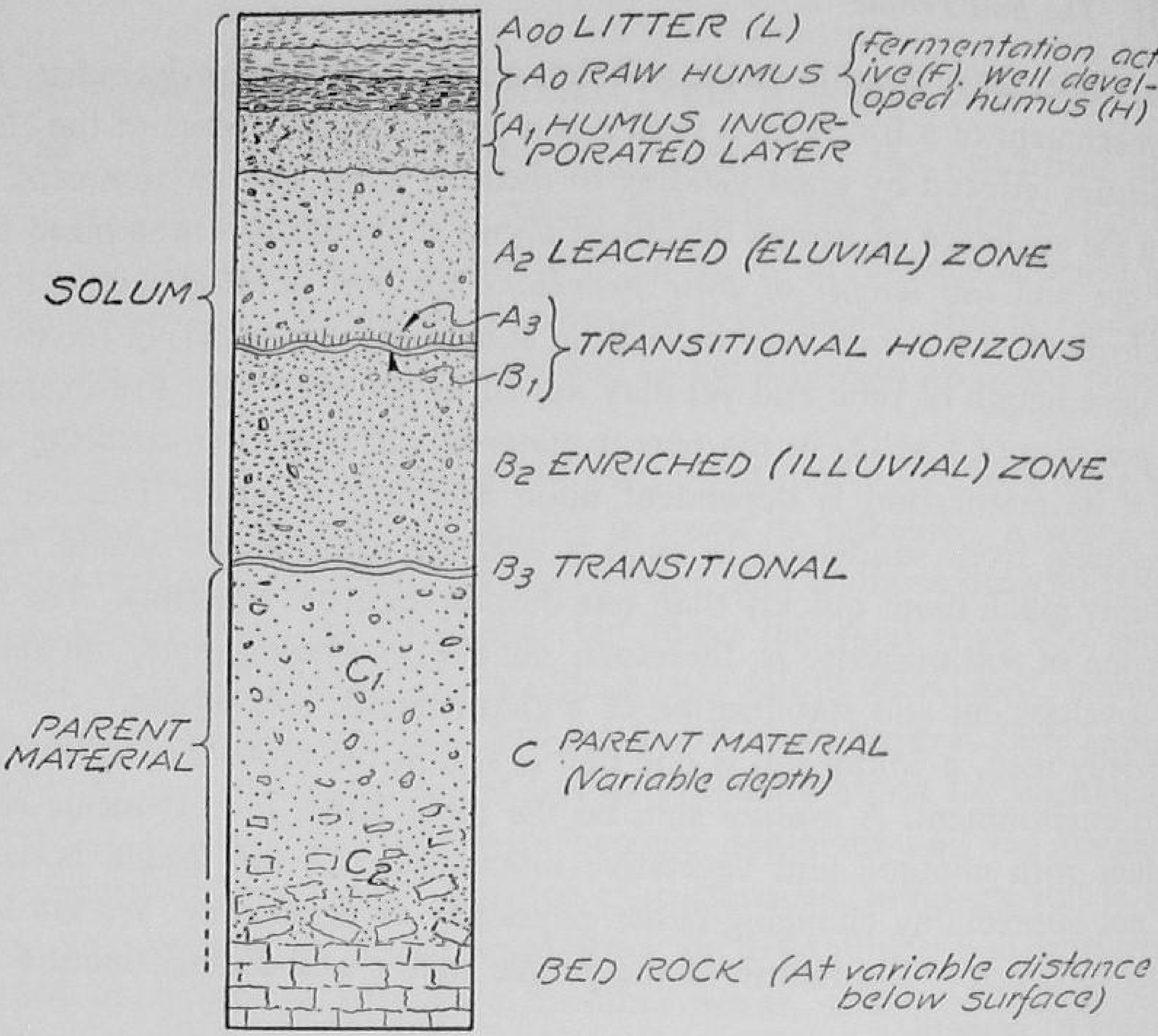

FIG. 12:1. *A theoretical soil profile showing all of the horizons usually distinguished. Any particular individual profile, however, generally exhibits clearly only part of these. Further details are as follows:*

A_{00}. *This horizon consists of loose relatively undecomposed organic debris. It is usually absent on grass lands but present on forest soils, especially those of temperate regions, and very abundant at certain times of the year.*

A_0. *A partially or fully humified organic horizon. It may be matted, fibrous, or granular. On grass land it is usually absent. On forest soils two distinct layers often may be distinguished—F, the zone of fermentation and H, a markedly humified zone.*

A_1. *A dark colored mineral horizon containing a relatively large amount of humified organic matter thoroughly mixed with the inorganic layer. In chernozems this layer is very thick; in podzols very thin or absent; and in other soils variable.*

A_2. *A light colored mineral horizon resulting from a leaching and bleaching action* (eluviation). *It is well developed and very noticeable in true podzols—the gray layer or* bleicherde *of these soils. It is absent from chernozems and certain other soils especially those of arid and semi-arid regions.*

A_3. *A transition layer, often absent. When it is present, it is more like A than B.*

B_1. *Also a transitional horizon and absent from most soils. But in true podzols it is often present as a characteristic zone of precipitated humus carrying considerable iron and aluminum.*

B_2. *A zone of accumulation* (illuviation) *especially of iron and aluminum compounds. It is particularly prominent in true podzols as a* reddish-brown *horizon. The hardpan* (ortstein) *of the podzol occurs here when present as does the* clay pan *of certain other soils. In arid region soils the* B_2 *is often characterized by special structural*

the surface, as is often the case in forests, it is referred to in mass as A_0. If it is thick enough to exhibit distinct layers, however, the terminology is extended to A_{00}. (See Fig. 12:1.)

The B group (illuvial) [3] comes next and includes the layers in which deposition from above, or even from below, has taken place. It is the region of accumulation, especially of iron and aluminum. Here also is concentrated the clay when this material washes downward from the surface layers. In arid regions calcium carbonate, calcium sulfate, and other salts may accumulate in the lower B. Its horizons are labeled in order downward as B_1, B_2, etc. The A and B horizons together are called the *solum,* that is, the portion of the profile developed by soil building processes as distinguished from the parent material immediately below.

The C horizon, or parent material,[4] is noticeably less weathered and is usually similar to or more or less identical with that from which the A and B horizons are derived. As yet it has not been subjected to soil building but its upper layers will in time become a part of the solum. Since the C horizon, especially the upper part, may show considerable chemical weathering, several zones may be distinguished. Generally, however, little attempt is made to differentiate within this horizon. For further details of the profile see the notes accompanying Fig. 12:1.

Horizons in a given profile. It is at once evident that the profile of any one soil probably will not show, even indistinctly, all of the horizons that

[3] Illuvial from *il* or *in,* meaning in and *luv,* washed. Although the B horizon is often referred to as the *subsoil,* this terminology may be technically incorrect. In some eroded soils and in soils with shallow A layers, the B horizon makes up at least part of the surface or plow layer. Also since the A horizon of certain soils is deep (24 inches or more) the subsoil may include a part of A in addition to B.

[4] *Parent material* in a broad, *geological* way refers to the unconsolidated mineral mass from which the solum has been developed. The past tense is implied since the parent has lost its identity in soil formation.

In a narrow and *contemporary* sense, however, the term is used to designate the unconsolidated material lying directly below the soil solum. However, this terminology can only be used when there is sufficient evidence that an appreciable proportion of the solum has been synthesized from mineral matter more or less identical with this basal horizon. The letter C, which is applied to the latter, connotates *parent material* in this *particular* present day *sense.* Any unconsolidated material below the solum that cannot be so characterized is referred to as D.

forms, frequently columnar or prismatic. In humid regions, silicate clays tend to accumulate in this horizon.

B_3. *A transitional layer. It may or may not be present.*

C. *Unconsolidated parent material similar to that from which the solum has developed. This may come from the bedrock below or it may have been transported from elsewhere and deposited on the bedrock.*

collectively are cited in Figure 12:1. The reasons are obvious. The profile may be immature or may be overly influenced by some local condition such as poor drainage, texture, or topography. Again some of the horizons are manifestly merely transitional and may at best be very indistinct. With so many factors involved in soil genesis, a slight change in their coordination may prevent the development of transitional layers. As a result, we can be sure of finding in any well-drained and uneroded mature soil only certain horizons. They are: A_0, if the land is forested; A_1 or A_2 depending on circumstances; B_2; and C. (See Fig. 12:1.) Conditions of soil genesis will determine which others are present and their clarity of definition.

When a virgin soil is put under cultivation, the upper horizons become the furrow-slice. The cultivation, of course, destroys the original layered condition of this portion of the profile, and the furrow-slice becomes more or less homogeneous. In some soils the A horizons are of sufficient depth so that not all of the A is included in the furrow-slice (Fig. 12:2). In cases, however, where the A is quite thin the plowline is just at the top of or even down in the B.

Many times, especially on cultivated land, serious erosion has occurred and as a result a *truncated* profile is encountered. As the surface soil was swept away, the plowline was gradually lowered in order to maintain a sufficiently thick furrow-slice. Hence the furrow, in many cases, is almost entirely within the B zone and the C horizon is correspondingly nearer the surface. Many farmers, especially in our Southern States, are today cultivating the subsoil without realizing the ravages of erosion. In profile study and description such a situation requires careful analysis.

12:4. FACTORS INFLUENCING SOIL CHARACTER[5]

So far, we have concerned ourselves primarily with the effects of weathering, both constructive and destructive, on soil formation. Forces of weathering, however, are but active expressions of a number of factors which largely control the kind of soil that finally develops. At least five such factors are apparent.

(1) *Climate* (particularly temperature and precipitation)
(2) *Living organisms* (especially the native vegetation)
(3) *Nature of parent material* — Texture and structure; Chemical and mineralogical composition
(4) *Topography of area*
(5) *Time* that parent materials are subjected to soil formation

[5] For a thought-provoking treatise on this subject, see Jenny, Hans, *Factors of Soil Formation*, McGraw-Hill Book Company, Inc., New York, 1941.

Climate. From an over-all standpoint climate is perhaps the most influential of these factors. In the first place it determines in no small degree the nature of the weathering that occurs. It has already been pointed out that temperature and precipitation exert profound influences on the rates of chemical and physical processes. These processes are in turn the essential means by which profile development is effected. Consequently, if allowed ample opportunity, climatic influences eventually tend to dominate the soil formation picture.

The effectiveness of climate is not altogether independently exerted, however. In fact, climatic influences are usually expressed through or in combination with the other factors. For example, much of the influence of

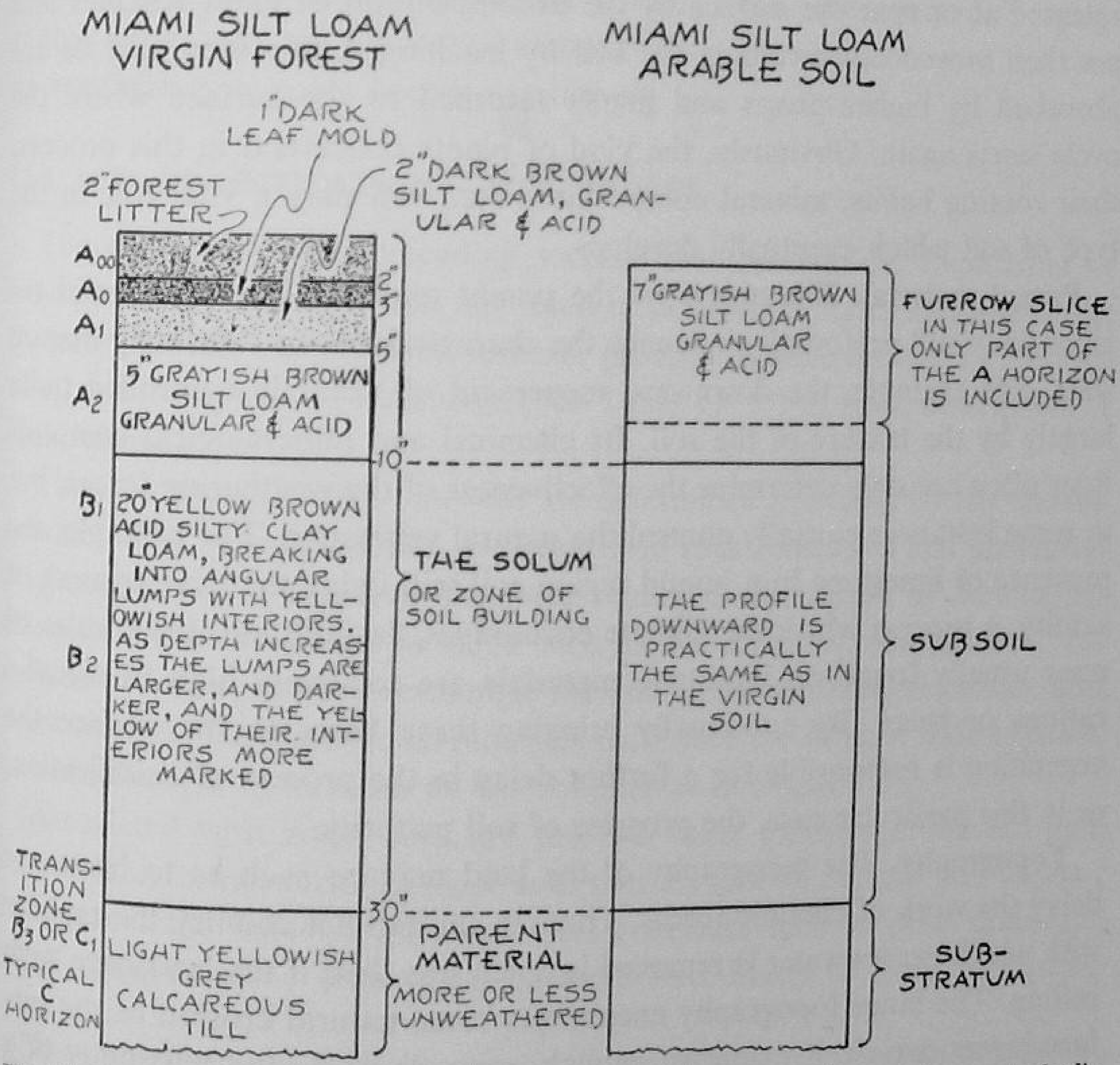

FIG. 12:2. *Generalized profile of the Miami silt loam, one of the gray-brown podzolic soils of eastern United States. A comparison of the profile of the virgin soil with its arable equivalent shows the changes that may be expected from cultivation. If erosion occurs, the original A horizon may disappear, at least in part, and some of the B horizon will be included in the furrow-slice. (After Baldwin, M., "The Gray-brown Podzol Soils of Eastern United States,"* Proc. and Papers of the First Internat. Cong. of Soil Sci., *4:276–282, 1927.)*

climate is due to the measure of control which it exercises over vegetation. Thus, in humid regions, plentiful rainfall not only encourages rapid chemical changes but at the same time provides an environment favorable for the growth of trees. The influence of these two factors on the kind of soil that develops cannot be overemphasized.

Vegetative cover. The vegetative cover native to a given region acts as a modifier of climatic influences. The role of the organic fraction of plant residues has already been emphasized (page 13). Inorganic salts associated with plants also play a vital part. The continual deposition at the surface of mineral elements brought up by plants from various depths within the soil is a part of what is essentially a cyclical process. These nutrients are released at or near the surface by the decomposition of plant residues and are then moved downward in the soil by leaching. Later they may be reabsorbed by higher plants and finally returned to the surface where the cycle starts again. Obviously, the kind of plants concerned in this process, their rooting habits, mineral composition, etc., will play a vital role in the type of soil which eventually develops.

Parent material. The nature of the parent material, even in humid regions, may still profoundly influence the characteristics of even fully mature soils. For example, the downward movement of water is controlled quite largely by the texture of the soil. Its chemical and mineralogical compositions often not only determine the effectiveness of the weathering forces, but in some instances partially control the natural vegetation. For example, the presence of limestone in a humid region soil will delay the development of acidity, a process which the climate encourages. In addition, the species of trees usually found on limestone materials are relatively high in metallic cations or bases. By continually bringing these bases to the surface the vegetation is responsible for a further delay in the process of acidification, or in this particular case, the progress of soil maturity.

Topography. The topography of the land may be such as to hasten or delay the work of climatic forces. Thus, in smooth flat country the rapidity with which excess water is removed is much less than if the landscape were rolling. The latter topography encourages some natural erosion of the surface layers, which, if extensive enough, may eliminate the possibility of a deep soil. On the other hand, if water stands for part or all of the year on a given area, the climatic influences become relatively ineffective in regulating soil development. Topography, therefore, is significant not only as a modifier of climatic effects, but often as a major control in local areas.

Time. The actual length of time that materials have been subjected to weathering plays a significant role in soil formation. Perhaps the best evidence of the importance of time may be obtained by a comparison of the soils of a glaciated region with those in a comparable area that was untouched by the ice sheet.[6] As a general rule, the influence of parent material is much more apparent in the soils of glaciated regions. This is due primarily to the fact that in many cases insufficient time has lapsed since the disappearance of the ice to permit the changes in the composition of the glacial deposit that are necessary for full maturity of soils.

It should not be inferred from the above, however, that mature soils are not found in glaciated regions. In fact, they are quite numerous in certain areas. If other conditions, such as the nature of the parent material, topography, slope, etc., are favorable, climatic influences dominate and the time of weathering in years becomes relatively less significant.

12:5. SOIL CLASSIFICATION[7]—SOIL ORDERS

The concepts in the preceding section have become the foundation of a system of soil classification now used in the United States and elsewhere. By means of this classification soils are grouped in three orders: (1) Zonal, (2) Intrazonal, and (3) Azonal. (See Table 12:1.) A brief description of each follows:

The characteristics of *zonal* soils are determined primarily by the climate in which they have developed. Differences in rock formation and geological origin are largely masked, or have been rendered subordinate by dominating climatic influences. Local features such as drainage, topography, etc., are such as to permit or even encourage the maximum influence of climate and vegetation. As the name *zonal* indicates these soils are of such wide expanse as to be thought of as more or less continental in extent.

Associated with zonal soils are the two other groups—*intrazonal* and *azonal*. The former includes those soils that, in spite of climate and vegetation, reflect the influence of some local condition such as poor drainage, alkali salts, or some other local characteristic. Many of their properties

[6] It is recognized that such a comparison is not entirely valid because of climatic differences. But if the comparison is made near the boundary of the southernmost glacial advance, these climatic differences may not be great.

[7] The subject of soil classification is quite thoroughly reviewed by a number of authors in *Soil Science*, Vol. 67, Feb., 1949. Even a casual examination of these articles will reveal not only the complexity of soil classification but also its evolutionary incompleteness.

Table 12:1. A Classification of Soils into Orders, Suborders and Great Soil Groups.[8] Each Great Soil Group is Subdivided into Numerous Soil Series and Soil Types. (See Sec. 12:19.)

Order	*Suborder*	*Great Soil Groups*
Zonal Soils	1. Soils of the cold zone	Tundra
	2. Light-colored podzolized soils of timbered regions	Podzol Soils Brown Podzolic Soils Gray-Brown Podzolic Soils Red-Yellow Podzolic Soils Gray Podzolic or Gray Wooded Soils [9]
	3. Soils of forested warm-temperate and tropical regions	A variety of Latosols are recognized. They await detailed classification
	4. Soils of the forest-grassland transition	Degraded Chernozem Soils Noncalcic Brown or Shantung Brown Soils
	5. Dark-colored soils of semi-arid, sub-humid, and humid grasslands	Prairie Soils (semi-podzolic) Reddish Prairie Soils Chernozem Soils Chestnut Soils Reddish Chestnut Soils
	6. Light-colored soils of arid regions	Brown Soils Reddish-Brown Soils Sierozem Soils Desert Soils Red Desert Soils
Intrazonal Soils	1. Hydromorphic soils of marshes, swamps, flats, and seepage areas	Humic-Glei Soils [9] (includes wiesenboden) Alpine Meadow Soils Bog Soils Half Bog Soils Low-humic Glei Soils [9] Planosols Ground-water Podzols Ground-water Latosols
	2. Halomorphic (saline and alkali) soils of imperfectly drained arid regions littoral deposits	Solonchak (or saline soils) Solonetz Soils (alkali soils) Soloth Soils
	3. Calcimorphic soils	Brown Forest Soils (Braunerde) Rendzina Soils
Azonal Soils	(No suborders)	Lithosols Regosols (includes dry sands) Alluvial

[8] Modified from Thorp, James, and G. D. Smith "Higher Categories of Soil Classification: Order, Suborder, and Great Soil Groups," *Soil Sci.*, 67: 117–126, 1949.
[9] New or recently modified Great Soil Groups.

are, of course, similar to those of the zonal soils with which they are associated but the characteristics resulting from local condition are dominant. Since such soils cross zonal boundaries, they are termed intrazonal. Azonal soils in marked contrast are those that are without profile characteristics. Most soils developed on recent alluvial and colluvial deposits belong in this group.

12:6. ZONAL SOILS—A GENERAL SURVEY

As the classification of soils is followed still further, it seems logical to first consider the zonal soils because of their wide expanse and world importance. As seen in Table 12:1 the *order* of zonal soils is further broken down into *suborders* on the basis of specific climatic and vegetative regions. Each of these suborders in turn is divided into *great soil groups* such as the *podzol, prairie,* etc. These great soil groups, because they are an expression of more specific conditions, will be the subject of much of the discussion that follows.

The classification of zonal soils, outlined in Table 12:1, is presented somewhat more simply by the drawings in Figure 12:3. Here the relationship among climate, vegetation, and some of the important zonal soils is illustrated. The diagrams are particularly helpful in the study of the soils of the United States since the general climatic differences shown in Figure 12:3 approximate those found in this country when going from the Rocky Mountain area eastward. It would be advisable to observe this figure carefully before considering the specific properties of the zonal soils.

In regions too cold for the growth of trees or grass and yet warm enough for some plant life, the vegetation which develops is known as *tundra.* (See Fig. 12:3.) This consists primarily of mosses, lichens, and shrubs. The tundra is found under both humid and arid conditions and the soils which develop are of little agricultural value.

In humid regions the native vegetation of zonal soils is predominantly forests. Within forested areas *podzols* or *podzolic* soils develop if the climate is temperate and moist, whereas *latosols* are formed in wet tropical or semi-tropical regions. These mature forest soils, as you would expect, are quite thoroughly leached. Consequently, they are usually definitely acid in the surface and there is no $CaCO_3$ remaining in the solum. An accumulation of iron and aluminum as well as silicate clays is common in the lower horizons. As the intensity of their weathering would suggest, profile layering in mature forest soils is quite distinct. Their native fertility

as a result of leaching is low compared to that of soils of drier regions.

In addition to the forest soils of humid regions, a second group of soils under forest cover should be mentioned. This group is the *Gray wooded* soils of western United States and Canada and certain other countries. Having developed under sub-humid to semi-arid cool climates, their characteristics resemble somewhat those of the podzols. They are, however, less drastically leached and hence are much less acid than the latter soils.

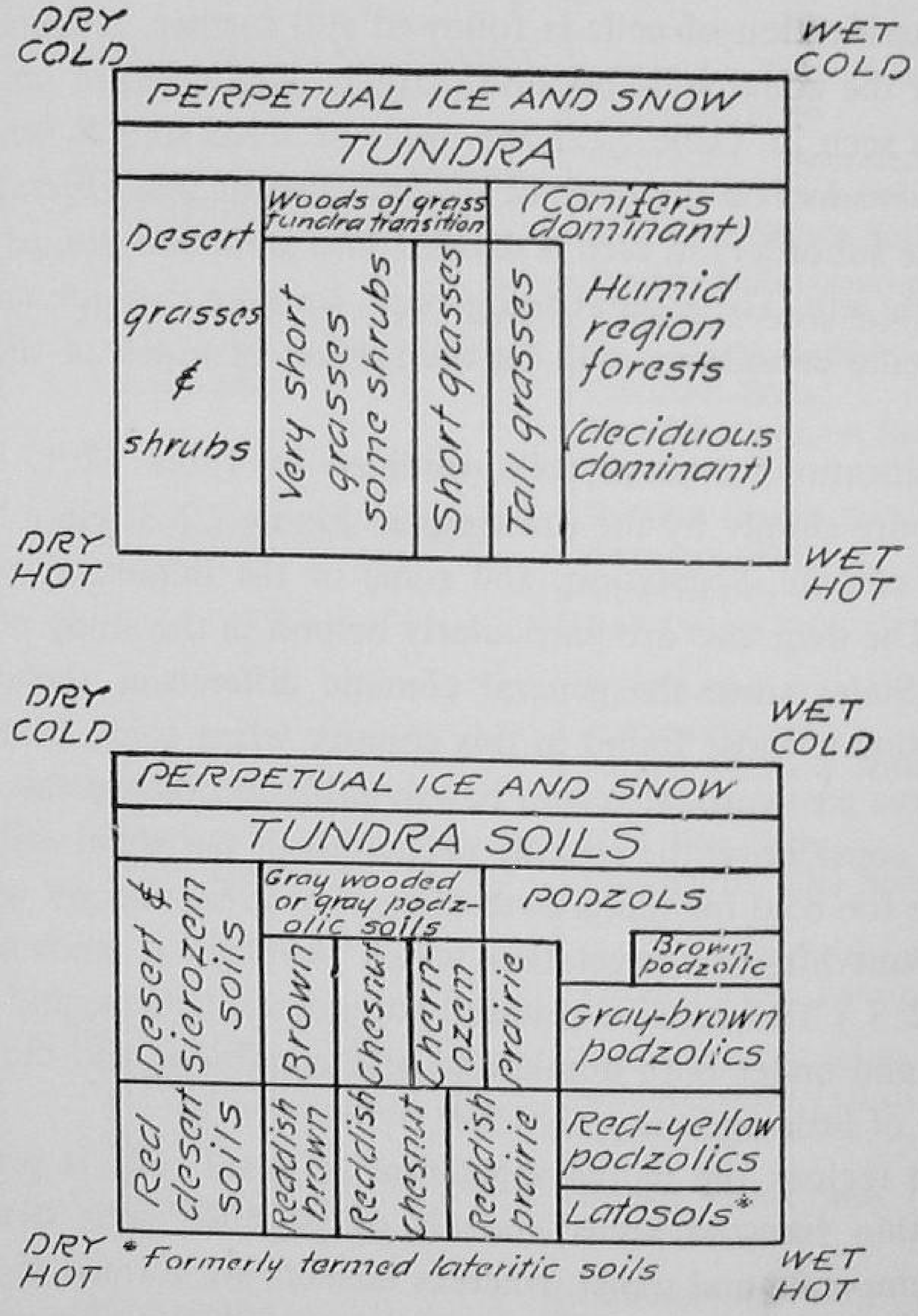

FIG. 12:3. Above—*a simplified diagram showing how the natural vegetation varies with climate.* Below—*a similar diagram indicating the relationship of zonal soils to climate. Note that soil boundaries correspond rather closely to those of the natural vegetation.*

The right to left successions of soils and vegetation shown in the diagrams approximate those that will be encountered when travelling from the east coast of North America to the Sierra Nevada and Cascade Mountains. Typical desert conditions occur in the inter-mountain regions west of the Rockies.

As one moves from eastern United States to regions of lower rainfall further west, the humid region forests are gradually replaced by grasslands. (See Fig. 12:3.) The so-called tall grasses which cover the *prairie soils* are found under climatic conditions which, although drier than those of some forested areas, are still considered humid. Consequently, these soils have some properties in common with forest soils and others in common with soils of the semi-arid grasslands. They have been subjected to considerable leaching, but their color and organic matter content and distribution resemble that of other grassland soils.

The *Chernozem* and *Chestnut* groups are developed under semi-arid conditions while the *Brown* and *Desert* soils are zonal representatives of arid regions. (See Fig. 12:3.) All these soils have developed under an annual rainfail of 25 inches or less. Due to the consequent lack of leaching there is usually a $CaCO_3$ accumulation at some point in the profile, usually in the upper C horizon. (See Fig. 12:7.) As the rainfall decreases this layer of calcium carbonate, underlain by more soluble salts such as $CaSO_4$, is found nearer and nearer the surface. Unlike humid-region soils, there is little translocation of iron and aluminum. These soils are variable in color primarily due to differences in organic matter content as well as differences in the processes of decay. As the annual precipitation becomes progressively less, grayish colors become more and more pronounced. Where the temperature is high, shades and tints of yellow and red occur. This accounts for such names as *reddish chestnut* and *red desert.*

In summary, it can be said that the properties of the zonal soils of the drier regions differ from those of humid region forest soils in the following major respects.

1. Their surface soil pH values are higher (usually near 7 or above).
2. Their nutrient status, particularly in respect to bases, is higher.
3. These soils are (except for the Chernozems) lower in organic matter and nitrogen in the surface horizons.
4. They nearly always contain a $CaCO_3$ accumulation at some point in the profile.
5. They usually exhibit a less distinct profile development.
6. Biologically, organisms are active at greater depths, but because of moisture deficiencies, less over-all microbial activity occurs in the profile of aridic zonal soils.

12:7. TUNDRA SOILS [10]

The zonal great soil groups will now be considered in order beginning with the tundra. (See Table 12:1.) The soils of this category are of little agricultural importance except as pasturage for reindeer and caribou. Consequently, they deserve hardly more than passing mention in spite of their tremendous expanse in northern Europe, Asia, and North America. Roughly 40 per cent of the Soviet Union is thus covered, an area equal to that of the whole United States.

These soils lie just north of the *podzolic* and *gray wooded* groups and, as might be expected, the transition from forests to the mosses, lichens, and shrubs of the northlands is most irregular. The accumulation of such organic matter gives a peaty surface covering over a bluish-gray, sticky and compact subsoil. Since the substratum, and sometimes even the subsoil, of the tundra remains frozen most of the year, a poorly drained boggy condition is sure to be the rule at certain seasons. Much heaving takes place with the alternate freezing and thawing, and explosive blisters sometimes occur. With the tundra soils are associated the muskeg peats, often with perpetually frozen subhorizons.

12:8. PODZOLIZATION [11]

Since, in addition to the true *podzols,* several of the other great soil groups are *podzolic* in nature, the process of podzolization should be thoroughly understood before proceeding further. This process, in its greatest intensity, requires certain conditions. Firstly, there must be an adjustment of temperature, rainfall, vegetation, and other factors which favors an abundant surface accumulation of organic matter called duff or *mor.* (See Figs. 12:4 and 12:6.) Forests are therefore the most common vegetation,[12] although mild podzolization sometimes occurs with grasses. Coupled with this there must be a type of organic matter decomposition that will develop *acids* and other substances of great solvent capacity. When podzolization is intense, fungi seem to be the major microorganisms engaged in the pro-

[10] See Nikiforoff, C. C., "The Perpetually Frozen Subsoil of Siberia," *Soil Sci.,* 26: 61–81, 1928, and Fuestel, I. C., A. Dutilly, and M. S. Anderson, "Properties of Soils from North American Arctic Regions," *Soil Sci.,* 48: 183–198, 1939.

[11] Joffe, J. S., *Pedology,* Rutgers University Press, New Brunswick, N. J., 1936, Chap. 9 and Kellogg, Charles E., *The Soils That Support Us,* The Macmillan Company, New York, 1941, pp. 138–149.

[12] A high proportion of coniferous trees, or other trees the litter of which has a low content of bases, is of considerable importance in hastening the podzolic process.

duction of humus, bacterial activity being at a minimum. (See Fig. 14:4.) In such an acid, low-calcium organic medium, earthworms are practically absent. pH values as low as 3.5 are often found in this accumulation, especially that of the H layer. (See Fig. 12:4.)

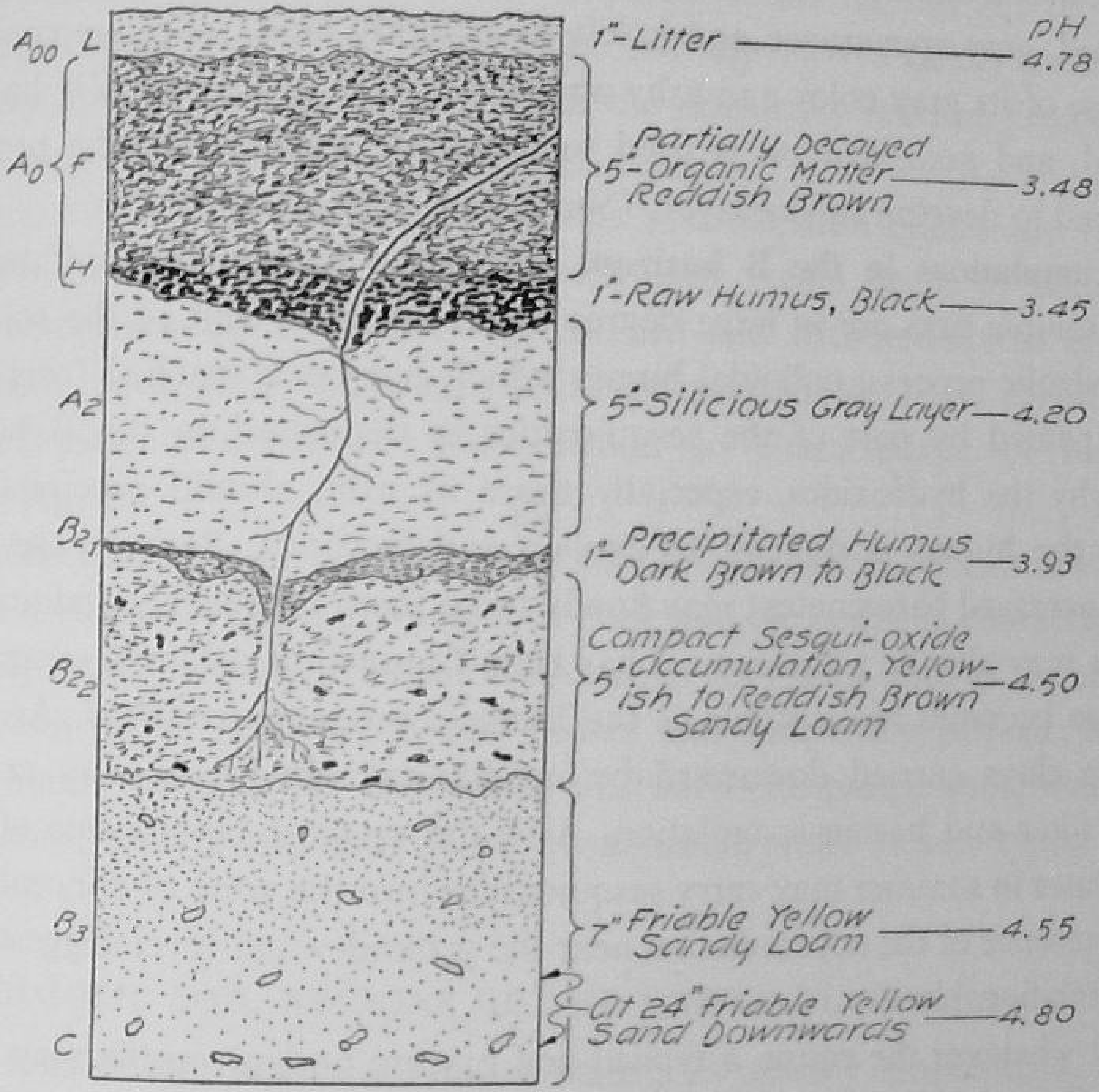

FIG. 12:4. *A well-developed podzol profile at White Lake Lodge, New York, on the southwestern edge of the Adirondack Mountains. The soil is a stony loam, forested with birch, hemlock, and spruce. Note the thickness of the organic layers (mor or duff), the depth of the gray silicious horizon (A_2), and the marked acidity of the whole profile, even the C_1. The layer of precipitated humus (B_{21}) is quite distinct. The letters L, F, and H refer to* litter, *zone of* fermentation *and* humus *layer.*

Acid leaching. If vigorous podzolization is to occur, sufficient moisture must be present to promote marked leaching. This process is, of course, greatly speeded up if the parent material is loose and open. Leaching carries the acids of the organic horizons downward through the mineral layers below, dissolving and entirely removing carbonates of all kinds. The colloidal complex of the A horizon thus becomes more or less saturated with hydrogen and hence it is rendered extremely acid. pH values of 4.0 to 4.5 are common in this leached layer.

Under the conditions described above, the colloidal complexes of the A horizon become unstable and break up. The iron and aluminum not already removed are carried away, probably in the sol condition. No doubt humic substances, other than organic acids, have something to do with this chemical eluviation. The A_2 horizon, thus drastically leached, assumes a bleached, gray appearance and is left in a highly acid, siliceous condition. Because of its gray color and ashy appearance the term *podzol*[13] has been applied, and *podzolization* is used to designate collectively the processes that tend to develop such a layer. (See Fig. 12:4.)

Accumulations in the B horizon. While the carbonates, sulfates, and other soluble salts are in large degree carried entirely out of the solum by the podzolic process, colloidal humus which has been leached from above accompanied by part of the sesquioxides is deposited in the B horizon. Just why the hydroxides, especially those of iron, should precipitate just below the humus is difficult to explain satisfactorily. Perhaps the somewhat increased base content may finally force them into a gel condition. The humus may also be a factor as it has been found that a humus-sesquioxide mixture becomes more stable as the humus content is reduced. Again the silicate clays carried downward by mechanical eluviation may act as a catch filter and hasten coagulation. Also the upward movements of capillary water in summer may carry sesquioxides into the zone of concentration. The presence of the accumulation near the ground-water level suggests some such relationship.

But whatever the cause, a typical and mature podzol profile may exhibit in the B zone three distinct horizons in order: a precipitated humus (B_{21}), a reddish-brown layer due to a concentration of the sesquioxides with some humus (B_{22}), and a yellowish horizon (B_3) below, which gradually merges with the parent material (see Fig. 12:4).

Podzols and podzolic soils. The preceding presentation has dealt with podzolization in its greatest intensity. This gives rise to a true *podzol* soil, the essential profile characteristics of which are shown in Figure 12:4. With the exception of the A_1, all the horizons associated with an ideal profile (Fig. 12:1) are found in a well-developed podzol.

The podzol soils gradually merge to the southward with those having a brown or gray-brown surface layer and an admixture of the organic matter with the A horizon. Under such conditions the gray siliceous layer becomes thinner and thinner until it disappears. The precipitated humus

[13] From the Russian *pod,* meaning "under" and *zola,* "ash."

zone is no longer evident, and the accumulation of iron and aluminum in the B horizon is less prominent. Moreover, the organic layer becomes more and more mixed with the mineral soil below until the A_0 is very thin, most of the organic matter being a part of the A_1. This layer, now called a *mull,* thus becomes very prominent at the expense of the A_0 and A_2, the latter changing from a gray to a brown color. We now have a mildly podzolized soil, very much higher in fertility than the drastically leached profile with its gray and acid A_2 horizon. (See Fig. 12:6.)

Under still warmer humid conditions podzolization effects are further modified. In the B horizons red and yellow colors begin to dominate. These colors are due primarily to oxidized and hydrated forms of iron. Apparently such soils, although definitely podzolized, have experienced the modifying influence of latosolization so characteristic of soils of warmer regions.

A marked change in profile also is found as progress is made toward a more arid climate. Forest gives way to grass and the podzolic characteristics gradually fade. Carbonates become evident in the profile and, as the rainfall lessens still more, they are found nearer and nearer the surface. In the United States the podzolic soils grade westward into prairie soils, then into chernozems, and finally into more pronounced aridic region types. (See Fig. 12:3.)

12:9. PODZOLIC SOIL REGIONS OF THE UNITED STATES[14]

The soils of northeastern United States, as already emphasized, show conclusive gradations from podzolic to latosol conditions southward, and from podzolic to aridic in a westerly and southwesterly direction. This merging is inevitable. As a result, six podzolic soil regions may definitely be distinguished. (See Table 12:1.)

True podzols.[15] The first, drastically podzolized, is designated as the

[14] For an excellent discussion of the soils of the various regions of the United States as to origin, profile characteristics, and agricultural importance, see Kellogg, Charles E., *The Soils That Support Us*, The Macmillan Company, New York, 1941. As might be expected, considerable progress has been made in soil classification since this book was published.

[15] As might be expected, various degrees and gradations of podzol formation occur. For instance, in many podzols the A_2 apparently rests directly on the B_{2_2}, which is especially high in iron. Such a profile is called an *iron podzol*. When organic matter is more abundant or rainfall heavier, a distinct layer of precipitated humus (B_{2_1} accumulates between the leached zone (A_2) and the B_{2_2}. This profile is called a *humus podzol*. In either case the B_{2_2} below is a more compact layer, comparatively high in precipitated iron and aluminum and reddish-brown or yellowish-brown in color. Some-

region of typical *podzol soils* because of the characteristic color of the A_2 horizon. These soils occur mostly in northern and northeastern United States. (See Fig. 12:5.) Their profile characteristics already have been explained. It need only be said further that the parent material is so drastically leached during soil formation and the upper layers are left so acid, that such soils are rather low in agricultural value except in certain cases. Once the organic matter is gone the slump in productivity is rapid. Most of these soils are best left in woodland. Only with certain crops, such as potatoes in Aroostock County, Maine, is their cultivation advisable.

Brown podzolic soils. Just south of the typical podzols in New England, New York, and elsewhere in northern United States is found a less drastically podzolized soil group of considerable importance in spite of its comparatively small area—the *brown podzolic.*[16]

Most of the properties of these soils are such that they can almost be considered as weak podzols. There is only a small amount of organic matter (A_0) on the surface of virgin soils. The infertile siliceous layer of the podzol (A_2) is absent or very faint. Consequently, the thin A_1 (2–3 inches) which contains a considerable amount of organic matter lies directly on the B horizon. Moreover, there is little evidence of cementation or clay accumulation in the B. Consequently, the brown podzolic soils are loose and well drained and, in spite of their acidity, are much better suited for agriculture than are the typical podzols. They are a transitional group of great importance in New England and play an important role in the agriculture of this section.

Gray-brown podzolic soils. The gray-brown podzolic soils which lie still further southward (Fig. 12:5) are also mildly podzolized. Due to differences in climate, vegetation, and parent materials, however, they present a profile somewhat different from the brown podzolic. The organic matter, mostly from deciduous trees, does not accumulate on the forest floor as a mat (mor or duff). It has largely become incorporated with the mineral soil (A_1) giving a *mull* layer several inches thick, within which a mild decomposition is occurring. The gray siliceous layer of the podzol is replaced by a gray or yellowish-brown horizon (A_2) from 5 to 12 inches thick. This

times this zone is very hard and impervious to water, a true hardpan. It is then known as an *Ortstein* layer. Conditions are now favorable for a gradual alteration in drainage which eventually produces a *half-bog* and finally a *bog* soil whose solum is almost entirely organic.

[16] See Lyford, W. H., "The Morphology of the Brown Podzolic Soils of New England," *Proc. Soil Sci. Soc. Amer.*, 11: 486–492, 1946.

horizon is characterized by a horizontal, platy structure, and as with the podzol, it is the zone of eluviation. In spite of this, however, considerable exchangeable calcium still occupies the colloidal complex. Consequently, these layers, especially the A_1, are not excessively acid. In fact, at times they are only mildly so. Bacteria and actinomyces are active as well as fungi, and earthworms are numerous.

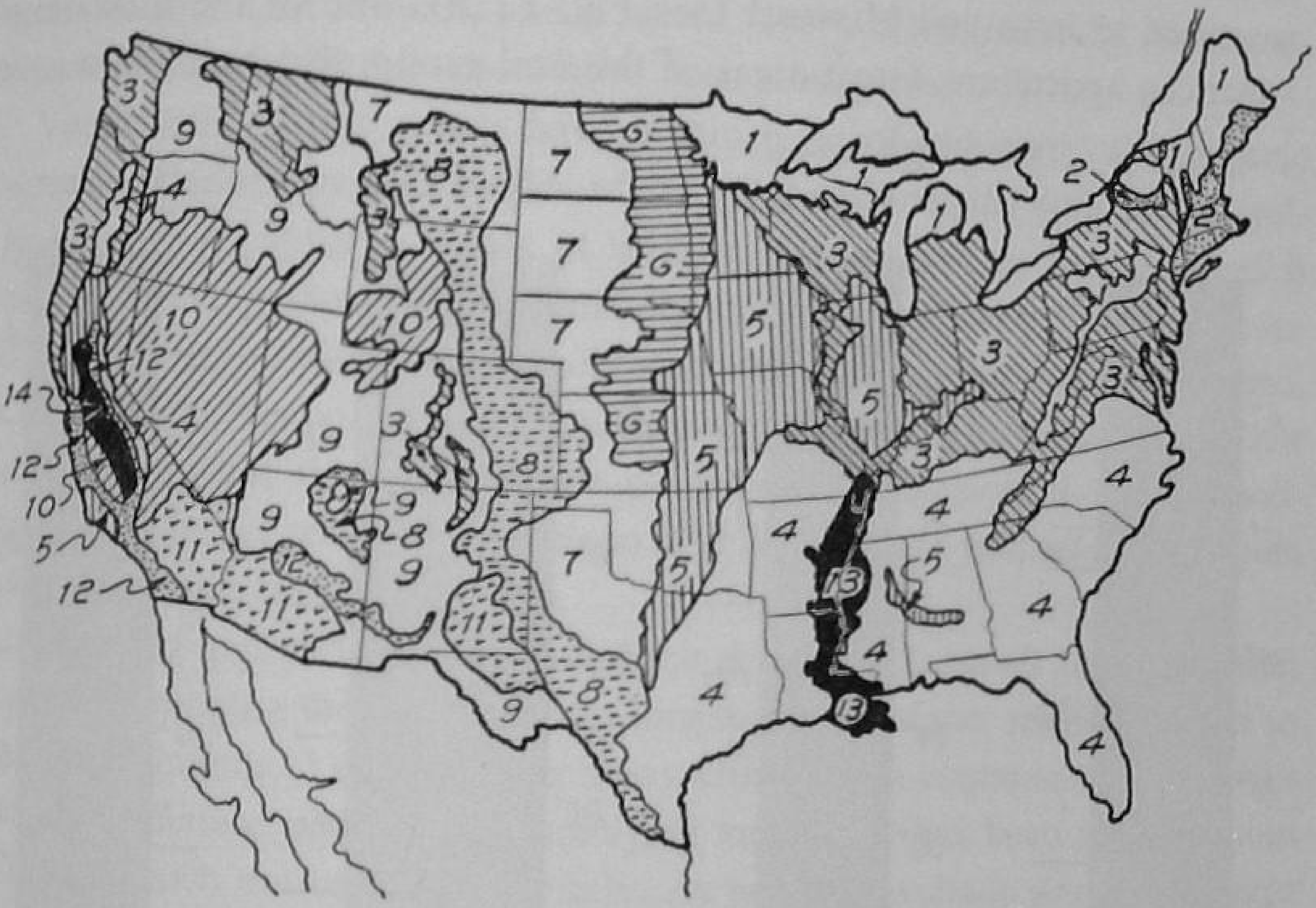

FIG. 12:5. A simplified map showing the major Great Soil Groups of the United States. (After Marbut and Kellogg.) The poorly drained soils in most cases are included with their zonal associates. The regions located are as follows:

1. *Podzol.*
2. *Brown podzolic.*
3. *Gray-brown podzolic.*
4. *Red and yellow podzolic (lateritic).*
5. *Prairie and reddish-prairie (Includes some Planosols & Rendzinas).*
6. *Chernozem.*
7. *Chestnut and reddish-chestnut.*
8. *Brown and reddish-brown.*
9. *Shallow soils (lithosols), mountain, upland, and valley.*
10. *Gray desert (Sierozem).*
11. *Reddish desert.*
12. *Non-calcic brown.*
13. *Mississippi alluvium.*
14. *Alluvium and outwash of the central valley, California.*

The B horizons of these soils show some accumulation of silicate clays and often possess a blocky structure that does not always facilitate drainage. Oxides of iron and aluminum also accumulate in this horizon. All in all, the gray-brown podzolic soils constitute a zonal group of great agricultural value. For further profile details see Figs. 12:2 and 12:6.

Although the fertility of the gray-brown podzolic soils is only medium, the climate under which they occur favors crops that assure stable agricultural conditions, especially in the United States. The farms are comparatively small, diversification of crops easy, and markets are close at hand. Opportunities for making a livelihood are such as to render the gray-brown podzolics, covering a great strip from the Middle Atlantic states westward to Iowa and Missouri (see Fig. 12:5), one of the bulwarks of American agriculture. Great areas of this soil group also occur in western

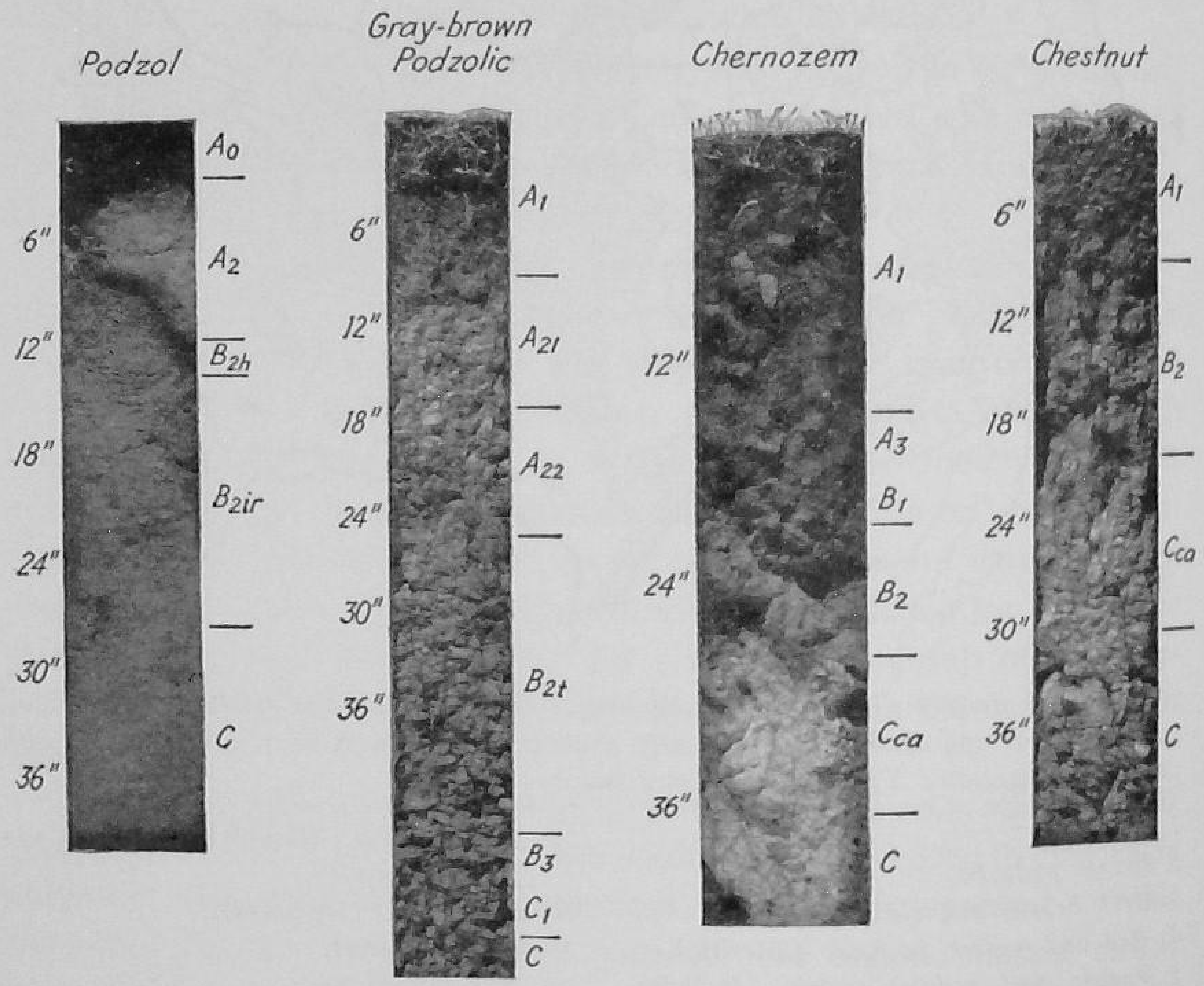

FIG. 12:6. *Monoliths of soil profiles representing four great soil groups. The process of podzolization is much more intense with the podzol than with the gray-brown podzolic soil even though both have developed under forest vegetation. Note the precipitated humus in the B_{2h} horizon of the podzol, below which iron and aluminum oxides have accumulated (B_{2ir}).*

In the case of the gray-brown podzolic soil, the A_2 is subdivided into two layers (A_{21} and A_{22}). Mild acid leaching has resulted in the formation of silicate clays which have accumulated in the B horizon (B_{2t}) of this soil.

The chernozem and chestnut have been subjected to calcification under grass vegetation. This accounts for the high organic content, noticeably present in the chernozem, and for the deep A_1 horizons. Note that the zone of $CaCO_3$ accumulation (C_{ca}) is found nearer the surface in the chestnut than in the chernozem.

Montana and northern Idaho. Besides, a wide belt extends down the coastal and valley regions of western Washington and Oregon and into California as far south as San Francisco.

Red-yellow podzolic soils. The red-yellow podzolic soils of the southern states (see Fig. 12:5) indicate clearly that the modifying influence of latosolization has been at work. These soils have originated under a mild climate, an abundant rainfall, and a mixed forest, often markedly deciduous. As a result, podzolic influences have been most genial.

Virgin soils of this group have a thin layer of unincorporated organic matter, underlain by 2–3 inches of A_1. The *red podzolic* soils have a yellowish gray A_2 several inches in thickness over a red or brownish-red B horizon. Having developed under slightly greater effective moisture conditions, the iron oxides in the *yellow podzolics* are more highly hydrated. Consequently, the colors are somewhat less brilliant. The A_2 is light yellow and is somewhat thicker than the corresponding horizon of the red podzolics. The heavy textured B horizon is yellow to light yellow, an indication of the hydrated state of the iron.

These red and yellow soils have been developed from all sorts of parent materials, ranging from granites to limestones and from residual debris to marine sediments. Yet they have many attributes in common. It is remarkable that climate and its accompanying vegetation has been able to mold them into such noticeable uniformity. As progress is made southward these soils merge so gradually into the semi-latosols as to make the line of demarcation very vague. In eastern United States they stand next to the gray-brown podzolics in importance. But, because of their climate, they balance rather than compete with the latter in agricultural production.

Prairie soils.[17] The fifth podzolic or perhaps semi-podzolic soil region in the United States is that of the *prairie* whose soils are classified as dark-colored grass lands. (See Table 12:1 and Fig. 12:5.) Its climate is much the same as that operative in the gray-brown podzolic soil region to the eastward. But because the native vegetation was tall grass instead of forest the soils are strikingly different. Under such a cover the organic matter, thoroughly mixed with the A horizon, is especially high. The leaching, while sufficient to remove the calcium carbonate from the solum, has not seriously impaired the natural fertility. This is the only large area of such

[17] For an excellent discussion of these soils, see Smith, Guy D., W. H. Allaway, and F. F. Riecken "Prairie Soils of the Upper Mississippi Valley," *Advances in Agronomy*, II: 157–205, 1950, A. G. Norman, editor.

soils in the world. Just why they are free of woods and whether they would become partially forested in time if undisturbed by man are mooted questions.

The abundant native grass cover of the prairie soil area has resulted in a deep, rich, dark-brown A horizon with a varied and active micro-organic flora. Southward, the color changes to reddish brown and the soils are spoken of as *reddish prairie* soils. The structure of the surface soil is decidedly granular, due to the influence of the grass cover. The exchangeable calcium is high, in spite of the definite acidity, and little downward movement of iron and aluminum has occurred. In places the presence of clay pans indicates considerable translocation of clay. The B horizon is brownish and grades into a parent material that often is rich in lime. Podzolic influences, modified by climate and vegetation, have been decidedly beneficial. The marked accumulation of humus and its dark color, both extremely noticeable to eastern eyes, are probably due, in part at least, to the hot dry summers which have impeded and modified microbial activities, so marked in spring and autumn.

This belt of prairie soils, extends latitudinally through the heart of the country, with the chernozems on the one hand and with the gray-brown podzolics on the other. They are uniformly fertile and, with the red and yellow soils of the South and the gray-brown forest soils of the East, control the agriculture of central and eastern United States if not of the nation.

Gray wooded soils. The sixth podzolic soil to be considered is the *gray wooded* or *grey podzolic* group of western United States and Canada. These soils are developed under forest cover, and a cool sub-humid to semi-arid climate. A semi-decomposed organic matter layer (A_0) is found and a very thin A_1 of mixed mineral and organic matter is present. The A_2 horizon like that of the gray-brown podzolic soils is somewhat leached and platy. (See Fig. 12:3.)

These soils, although definitely podzolized, are not so thoroughly leached as their humid region equivalents. Consequently, the soils usually are not as acid, pH values as high as 7.0 in the B horizon frequently being encountered.

12:10. FORMATION OF LATOSOLS[18]

Under the abundant rainfall and high temperatures of the tropics and semi-tropics, weathering forces work faster and carry their influence to greater extremes than in temperate regions. Here there has been no glaciation to interrupt the process and the country rock and the regolith have been subjected to drastic decomposition. Hydrolysis, as well as oxidation, has been extremely intense and silicate minerals have quickly succumbed. In many parts of the tropics wet and dry seasons alternate, which no doubt greatly intensifies chemical activities, especially those of the organic matter. The process which is responsible for the formation of these soils is termed *laterization*, or perhaps more correctly, *latosolization*.[19]

The process and its results. In the genesis of latosols the soluble bases, such as calcium, magnesium, potassium, and sodium, are quickly released. Due to the mobility of these cations the pH is near 7. This condition of low acidity is furthered by the rapid decay of organic residues and the immediate release of the bases in organic combination. As a result, the solubility of the *silica* is encouraged and that of the *iron, aluminum,* and *manganese* retarded. If drainage is at all satisfactory, intense oxidation occurs. Thus, as weathering proceeds, red or yellow parent materials, high in the sesquioxide and low in silica, result. The extent of silicon removal and sesquioxide accumulation is remarkable. In Cuba, for example, a soil containing 1.8 per cent of SiO_2 and 71.1 per cent of Fe_2O_3 has developed

[18] A few of the more important articles dealing with tropical soils are:

Campbell, J. M., "Laterite, Its Origin, Structure and Minerals," *Mining Mag.*, 17: 67–77, 120–128, 171–179, and 220–229, 1917.

Bonnett, Juan A., "The Nature of Laterization as Revealed by Chemical, Physical and Mineralogical Studies of a Lateritic Soil Profile from Puerto Rico," *Soil Sci.*, 48: 25–40, 1939.

Hardy, F., and G. Rodriques, "Soil Genesis from Andesite in Grenada, British West Indies," *Soil Sci.*, 48: 361–384, 1939.

Carroll, D., and N. K. Jones, "Laterite Development on Acid Rocks in Southwestern Australia," *Soil Sci.*, 64: 1–16, 1947.

Humbert, R. P., "The Genesis of Laterite," *Soil Sci.*, 65: 281–290, 1948.

[19] Technically speaking, the term laterite refers specifically to a particular cemented horizon in certain latosols which, when dried becomes very hard and brick-like (thus, Laterite from the Latin *later*, brick). Therefore, *latosolization*, or some similar term would seem more applicable to the general process of soil formation in tropical and sub-tropical regions. See Pendleton, R. L., and S. Sharaswana, "Analyses of Some Siamese Laterites," *Soil Sci.*, 62: 423–440, 1946; and Kellogg, C. E., *Preliminary Suggestions for the Classification and Nomenclature of Great Soil Groups in Tropical and Equatorial Regions*, Commonwealth Bur. of Soil Sci., Tech. Communication No. 46: 76–85, 1949.

from parent material showing 41.9 per cent of SiO_2 and only 7.8 per cent Fe_2O_3.[20]

Because of the intensity of tropical weathering the regolith often becomes very deep and when a soil develops the B horizon usually extends many feet below the surface. Original differences due to the character of the country rock are often practically eliminated by the vigor of the chemical processes. The oxidation and hydration of iron and aluminum during latosol formation is, of course, intense above the water table and red and yellow hydrous oxide clays are the final product. Naturally no calcium carbonate is present. Iron concretions are found which are indicative of some translocation of the sesquioxides. In fact, where drainage is restricted soft deposits of these compounds often occur at or near the water table. In some countries these are cut out in conveniently sized blocks, which harden when dry and thus make excellent building material. A true laterite[21] always exhibits this layer.

The process of latosolization is so intense and leaching is so thorough that the *hydrous oxide* clays that develop are very low in exchangeable bases. In spite of this, however, the resulting latosols usually are not extremely acid or even moderately so. Due to the exceedingly low cation exchange capacity of the hydrous oxide clays, the bases present, even though small in amount, are able to maintain a relatively high percentage base saturation. The pH is therefore held at a comparatively high level, often near 7.

12:11. LATOSOLS[22]—CHARACTERISTICS OF

It is not difficult to forecast some of the characteristics of a zonal and well-developed latosol. A red or yellow color, especially in the B horizons, is a foregone conclusion. However, the surface soil, if uneroded, often is brown or gray. In other cases the red or yellow color dominates the surface

[20] Bennett, H. M., and R. V. Allison, "The Soils of Cuba," *Tropical Plant Research Foundation,* Washington, D. C., 1928, p. 2.

[21] A *laterite* soil is therefore only one of the varieties of *latosols* found in humid tropical regions.

[22] *Latosol* is the term applied to the suborder which includes soils of "tropical and equatorial regions having their dominant characteristics associated with low silica-sesquioxide ratios of clay fractions, low base-exchange capacities, low activities of clay, low content of most primary minerals, low content of soluble constituents, a high degree of aggregate stability and (perhaps) some red colour." See Kellogg, C. E., *Preliminary Suggestions for the Classification and Nomenclature of Great Soil Groups in Tropical and Equatorial Regions,* Commonwealth Bur. of Soil Sci., Tech. Communication No. 46, 1949, p. 79.

soil. This is likely to be the case when the parent material was basaltic. Also, enough erosion may have occurred, especially on cultivated lands, to bring some of the bright red or yellowish subsoil into the furrow-slice.

Another latosolic characteristic of outstanding importance is the peculiar granular condition that is developed and which promotes excellent internal drainage. Moreover, hydrous oxide clays do not possess the plasticity and cohesion that characterize the silicate clays of temperate regions. This allows the cultivation of typical latosols immediately after a heavy rain with little danger of generating an unsatisfactory physical state. In fact, latosols are utilized for agriculture under a weight of rainfall that would render siliceous soils utterly unworkable.

Typical latosols, as already stated, are low in cation exchange capacity compared to representative temperate-region soils. This is due in part to their lack of organic matter and in part to the nature of their hydrous oxide clays. Moreover, they are extremely deficient in exchangeable bases and in available nutrients in general. This means that their fertility level is very low. Hence, virgin soils, unless precautions are taken, are soon depleted in fertility when put under cultivation. Such soils usually require liberal fertilization if plant culture is to be at all intensive.

One disadvantage of the high content of sesquioxides is in respect to the efficiency of superphosphate. The iron and aluminum tend to render the phosphates of the fertilizer not only insoluble but very unavailable to crops. (See page 477.) For this reason rock phosphate, which is not so readily affected in this way, can be used to advantage. Some latosols are moderately or even strongly acid but not so intensely so as a silicate clay would be at the same percentage base saturation. These soils usually respond to lime even when applied in small amounts, as well as to commercial fertilizers.

Since humid-tropical and humid-semi-tropical climates merge more or less gradually into arid as well as into humid-temperate conditions, latosolization varies accordingly. All sorts of profile types may thus be found corresponding to climatic gradations. Indeed, it is often difficult to decide whether a given soil is essentially latosolic or podzolic. Thus, the red earths and red loams of the Mediterranean regions are considered by some to be progressively transitional. Without a doubt this is true for the red and yellow soils of our Southern States.

It is not to be inferred, however, that all soils in the tropics are latosols. Alluvial soils of all kinds occur as well as colluvial and fan debris. These

may show very little latosolization. Moreover, at the higher elevations podzolization is often the dominant type of soil genesis.

In Europe, latosols are found in southern France, Spain, Italy, and Greece. They also are typically developed in Central America, Mexico, Puerto Rico, Cuba, and other islands in the Caribbean Sea. In northern South America, India, Burma, Thailand, Java, Borneo, Sumatra, and contiguous regions, latosols are common, while on the islands of the central Pacific, red earths are abundant. The latosols of Hawaii have received especially careful study. Originally forested, latosols will grow many kinds of tropical and semi-tropical crops—sugar cane, rubber, coffee, bananas, and pineapples being common products.

12:12. CALCIFICATION

In the forested regions of humid eastern United States the process of podzolization dominates in soil formation. As one moves westward to areas of lower rainfall, however, this process is gradually replaced by that of *calcification.* The prairie soil area represents very well the transition zone in which both of these processes have been and still are active.

As suggested by the term calcification, this process yields a soil sufficiently high in calcium to give a fairly high percentage base saturation. Climate, and its resulting vegetation, are largely responsible for this situation. (See Fig. 12:7.) The rainfall in these areas is insufficient to leach much of the calcium and other divalent cations from the soil profile. Only in the upper horizons are the soils even mildly affected in this way.

Moreover, soluble constituents leached from the surface horizons are not removed from the profile. They are only moved to the lower horizons. Thus, a zone of accumulation of $CaCO_3$ occurs at a depth approximating the average penetration of the rain waters. On the drier soils, the more soluble calcium sulfate will also accumulate, usually below the zone of carbonate concentration. Even soluble salts of sodium and potassium may be present at the lower depths of the zonal soils of the arid regions.

It should be emphasized that even a considerable removal of soluble salts from the upper horizons of these soils does not yield excessively acid conditions. In fact, the surface horizons are at most mildly acid. In the drier regions the surface soils are commonly neutral or mildly alkaline. The percentage base saturation, even in the surface of such soils, is very high, due primarily to the large quantities of adsorbed calcium present.

The native vegetation, which ranges from grasses to desert shrubs, has

contributed to the progress of calcification. The grasses are particularly effective in returning bases to the surface of the soil. The extensive root systems of these plants also supply large amounts of organic matter. The humus that develops seems to be effective in stabilizing the soil colloids when adequate calcium is present. This prevents the downward movement of the finer materials, a process so characteristic of podzolization.

12:13. SOILS OF SEMI-ARID AND ARID REGIONS OF THE UNITED STATES [23]

Chernozems. Moving westward from the prairie soils of the United States the first great soil group to be encountered is that of the *chernozems.* (See Figs. 12:3 and 12:7.) Here calcification is dominant. The rainfall ranges from 15 to 25 inches annually and the native vegetation is mixed grass. While the precipitation is sufficient to support a vigorous growth of herbaceous plants, it is not heavy enough to leach through the profile. As a result, calcium carbonate accumulations usually occur in the upper C horizon which, therefore, is mildly alkaline and usually grayish or yellowish-brown with white spots or blotches of precipitated calcium carbonate. Under this lime accumulation lenses of gypsum are often found.

The A_1 horizon of a typical northern chernozem is black [24] due to the accumulation and decay of organic matter under scanty rainfall and hot dry summers.[25] This horizon is surprisingly deep, often 12 to 15 inches. (See Fig. 12:6.) In reaction it usually is neutral or even somewhat acid. Its granular structure is one of its outstanding physical characteristics. The depth to which the organic matter has penetrated possibly is related to the high-percentage base saturation, since humus dominated by calcium is considered to be more mobile than that carrying large amounts of adsorbed hydrogen. The amount of extremely black pigment present may also be related to the percentage base saturation.

A typical chernozem surface soil is surprisingly high in mineral nutrients as well as in nitrogen and sulfur. A chemical analysis has already been

[23] For a recent and well written coverage of irrigated soils of arid regions see Thorne, D. W., and H. B. Peterson, *Irrigated Soils, Their Fertility and Management,* The Blakiston Company, Philadelphia, 1949.

[24] *Chernozem* means black earth.

[25] The chernozem soils, especially those under a cool climate, receive sufficient rainfall during the spring and fall to encourage abundant grass. The summer drought checks rapid decay and thus the organic matter tends to accumulate in large amounts. Such a climatic control, in the presence of abundant calcium, seems to promote a type of decay that results in the production of a very black humus. The same explanation may be made for the northern prairie soils of the United States.

cited (see page 28) which fully supports these statements. On the basis of nutrient content the chernozems are the most fertile soils of large area in the United States. Because of low uncertain rainfall, however, they do not consistently produce so much as the corresponding prairie soils. The southern chernozems are usually lower in organic matter, lighter in color, and have reddish or yellowish subsoils. (See Fig. 12:6 for contrast with a typical podzol.)

Chestnut and brown soils. The *chestnut* and *brown* soil groups lie, in the order named, between the chernozem belt and the Rocky Mountains. They are the principal soils of the Great Plains. (See Fig. 12:5.) With a rainfall of only 10 to 15 inches annually, the vegetation is mostly of a steppe type. Due to the scanty precipitation such soils are much lower in organic matter than are the chernozems and the layer of carbonates is nearer the surface. Thus, the surface layers are neutral or even alkaline. Gypsum also is likely to be present in the subsoil. These soils, as well as the chernozems, are used for cereal production but non-irrigated agriculture is hazardous because of the low and variable rainfall. The plowing of such soils has increased wind erosion and has magnified the dust storms that in recent years have menaced the agriculture of the Middle West. The dust bowls of Texas, Oklahoma, Colorado, and Kansas, and of the Dakotas and Nebraska lie in these soil regions. (See Fig. 9:7.) Much of this extensive area should be in range and again under the protection of native vegetation.

The comparative characteristics of the *chestnut, brown* and *chernozem* soils are illustrated in Figure 12:7. All three great soil groups have developed under grasses. With decreasing rainfall, however, the shorter grasses dominate the vegetation. Profile development is less marked and organic matter content becomes more scanty as the annual precipitation decreases. The depth at which carbonate accumulations are encountered is much less in the soils of arid regions. For a *chestnut* profile see Figure 12:6.

Under warmer conditions, the characteristics of grassland soils, and particularly their colors, are somewhat different from their temperate region equivalents. The black and brown colors so common in the northern plain soils in this country give way to browns and reddish browns as one moves southward. The higher temperature apparently encourages the oxidation of iron and at the same time results in a lower organic matter content of the surface layers. The names associated with the great soil groups in these warmer regions—*Reddish-prairie, Reddish-chestnut* and

Reddish-brown (see Fig. 12:3 and Table 12:1)—reflect this color change.

Desert soils. When climatic conditions are so arid that grasses will not persist, desert shrubs become the natural vegetation. Under these conditions three zonal great soil groups are found: (1) *Sierozem* (Gray Desert), (2) *Desert,* and (3) *Red Desert.* The Sierozems develop under slightly higher moisture conditions than the desert soils, and are found quite

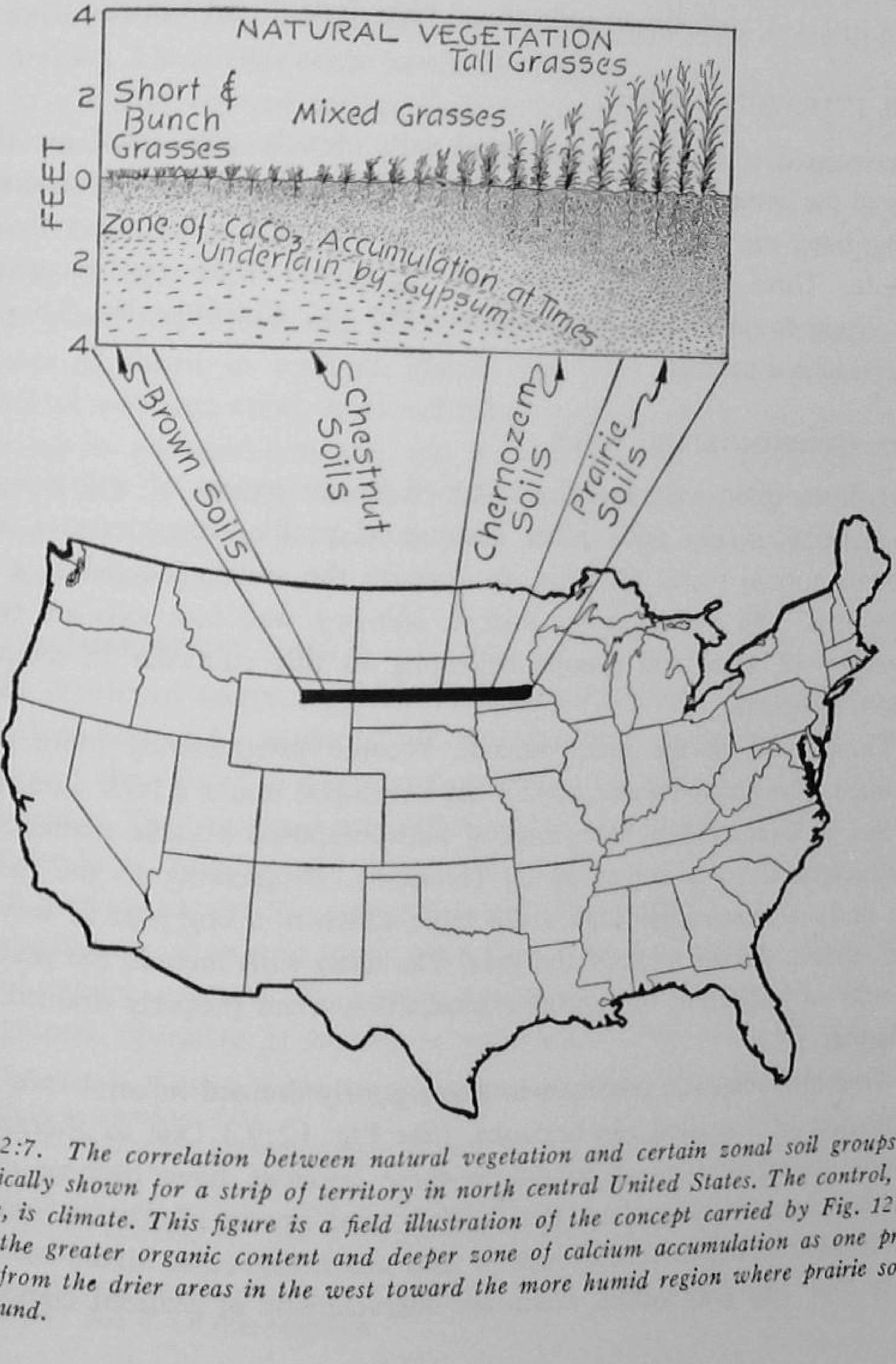

FIG. 12:7. The correlation between natural vegetation and certain zonal soil groups is graphically shown for a strip of territory in north central United States. The control, of course, is climate. This figure is a field illustration of the concept carried by Fig. 12:3. Note the greater organic content and deeper zone of calcium accumulation as one proceeds from the drier areas in the west toward the more humid region where prairie soils are found.

extensively in the intermountain region west of the Rockies. The vegetation on the desert soils is even more scanty than that of the sierozems and consequently much wind erosion occurs.

The *red desert* soils are found in southwestern United States under a warm to hot arid climate. As is the case with the Sierozem and desert soils, there is a layer of $CaCO_3$ accumulation under the surface horizon. This $CaCO_3$ layer is frequently cemented, giving rise to a hardpan. Except when irrigated, such desert soils are of little agricultural value.

12:14. INTRAZONAL SOILS

Associated with each of the zonal soils already considered are those soils of the *intrazonal* order. (See Table 12:1.) The major characteristics of the latter are largely determined by some local feature rather than by climate. Three major suborders of intrazonal soils are recognized: (1) *Hydromorphic,* (2) *Halomorphic,* and (3) *Calcimorphic.* They will be considered in order.

12:15. HYDROMORPHIC SOILS

Hydromorphic soils are characterized by an excess of soil moisture. Drainage is usually poor either because of profile characteristics which prevent normal water filtration, or because the soil is located in a low-lying area. The *ground water podzol, half-bog,* and *bog* soils are typical examples of great soil groups belonging to this suborder in temperate forested regions.

These soils, in the order named, become progressively more poorly drained. The ground water podzol has developed under a high water table. It has an exceptionally deep mat of undecomposed organic matter and is characterized by a cemented B_2 (ortstein). Progressing to the half-bog we find an increasingly high water table which in a bog is at or very near the surface during most of the year. The latter soils include the peats and mucks so important in vegetable production when properly drained. (See Chapter 13.)

One characteristic common to many poorly drained mineral soils is the presence of so-called *glei* horizons. (See Fig. 12:9.) Due to alternate periods of dry and moist conditions these horizons have become mottled with irregular colorations. Red, yellow, and brown streaks or spots are indicative of the oxidized forms of iron and manganese. Mixed with these are blue and gray colors which are characteristic of reduced compounds.

This mottled condition is looked for in the diagnosis of poorly drained soils.

Two hydromorphic soil groups found in *humid grasslands* are of special interest and importance. These are the *Wiesenboden*[26] and the planosol groups. Although the Wiesenboden group is found only under grass or sedges, planosols occur frequently in forested areas as well.

The Wiesenboden group is encountered primarily in association with the zonal prairie soils, which they resemble in many respects when properly drained. These soils occur in relatively flat areas of restricted drainage and have a dark colored surface horizon which is usually near neutrality. When drained, the productivity of the Wiesenbodens is high since their poor drainage is due to location rather than to clay pan development. The contrast between a Wiesenboden and a prairie profile can be seen by referring to Figure 12:8.

The *planosols,* which are poorly drained upland soils, occupy great stretches of prairie in southern Illinois and Iowa and northern Missouri as well as scattered areas in humid forest regions. These soils have been subjected to podzolization and are characterized by a heavy clay pan. Their surface is strongly leached and, due to their profile restrictions, they are not nearly as productive, even when artificially drained, as are their zonal associates.

12:16. HALOMORPHIC SOILS[27]

Soils developed under imperfect drainage conditions in arid regions are often characterized by abnormal salt concentrations in the upper horizons. Because of the effects of salts on their properties, these soils are termed *halomorphic*. They are most generally found in association with the chernozems, chestnuts, browns, and desert soils, and as a group are commonly, though perhaps incorrectly, referred to as "alkali soils."

Solonchak or *saline* soils result when there is an accumulation of soluble salts of sodium, calcium, magnesium, and potassium in the upper horizon. The process operative is known as salinization. The anions found are

[26] These are included in the humic glei soil group in Table 12:1 and are sometimes referred to as meadow soils.

[27] The classification presented here is used by the United States Department of Agriculture, Soil Survey Division. A newer and somewhat modified classification designed to evaluate soils in terms of plant response has been proposed by the United States Salinity Laboratory. This is discussed by Haward, H. E., and C. H. Wadleigh, "Plant Growth on Saline and Alkali Soils," *Advances in Agron.*, 1: 1–38, A. G. Norman, Ed., Academy Press Inc., New York, 1949. This classification is discussed on page 413 and ff. of this textbook.

mostly the chloride and sulfate with some carbonate and bicarbonate. The surface of a solonchak often is irregularly covered with a white crust of salts. (See Fig. 14:6.) These salts have been carried upward by capillarity and have remained when the water evaporated. As a result, solonchaks are commonly called *white alkali* soils.

Since the exchangeable ions of solonchaks are dominantly calcium and magnesium with relatively low amounts of adsorbed sodium, these soils are only slightly alkaline, their pH seldom rising much above 8. However, their high salt concentration prevents dispersion of the soil granules. Consequently, the physical condition of most solonchaks is not unfavorable for agricultural utilization. In spite of this, however, crop production on these soils is possible only after drainage is installed and the salt concentration lowered. (See Fig. 8:5.)

The drainage of a solonchak under conditions which bring about a depletion of exchangeable calcium and magnesium often will allow a marked increase in the sodium adsorbed by the soil colloids. Such a change results in the formation of a *solonetz* soil. Under the influence of sodium saturation and an excess of sodium carbonate, a high pH results. The soil colloids, both inorganic and organic, become dispersed and tend to move slowly down the profile. The dark color of the salty surface crust that often is observed is due to the dissolved organic matter. This accounts for the common name "black alkali" applied to these soils. The process of the formation of solonetz soils is aptly termed *solonization.*

The profile which develops as a result of this process is quite unique. Underneath a very thin friable surface horizon is found a dark horizon of hard clay. This zone has a characteristic columnar structure (see page 65) and makes a solonetz easy to identify. Solonetz soils are very unproductive due to their toxic chemical properties and poor physical condition. They can often be reclaimed, however, by proper management.[28]

It should be pointed out that the mere draining and leaching of a solonchak does not always result in a solonetz soil. If the content of exchangeable calcium and magnesium remains high after drainage, the soil will quite likely remain productive. The practice of irrigating white alkali soils with low sodium and low carbonate containing waters has been followed successfully for years without ill effects.[29]

[28] Methods of managing alkali soils are considered in Chapter 14, page 417 and ff.
[29] For the importance of low carbonate and bicarbonate contents, see Eaton, F. M., "Significance of Carbonates in Irrigation Water," *Soil Sci.*, 69: 123–133, 1950.

On the other hand, if improved drainage is maintained in the case of a solonetz it may eventually become leached thoroughly enough to allow the formation of a *soloth*. This soil has an acid light-colored surface horizon over a heavy dark brown B. Moreover, the excess colloids have been removed from the A horizon. These soils can be used essentially in the same way as their zonal associates.

12:17. CALCIMORPHIC SOILS

The characteristics of *calcimorphic* soils are largely due to the high lime content of their parent materials. *Brown forest soils* of the humid east and their grassland equivalents, the *Rendzinas,* are the two soil groups commonly recognized. (See Table 12:1.) The surface soils of both are at least neutral if not alkaline. Brown forest soils are dark brown in the surface and gradually grade into the gray calcareous parent material. There is little profile layering compared to zonal soils in the same region. Brown forest soils apparently are of much greater importance in Europe than in America.

Rendzinas are rather thin dark-colored grassland soils developed from soft lime rocks. The famous *Black Belt* extending northwestward across Alabama into Mississippi is the best known area in the United States. (See Fig. 12:5.) These soils are often subject to erosion damage, which is particularly serious due to their shallow depth.

12:18. AZONAL SOILS

The characteristics of azonal soils are determined, not by the climate or any particular soil forming process but rather by the nature of their parent material. Three groups are commonly recognized—*lithosols, regosols,* and *alluvial.* (See Table 12:1.) The first give rise to thin surface soils over bedrock. They are commonly found on steep slopes, show little soil development, and in general are not of significance agriculturally.

Regosols are also very young soils and are located on deep unconsolidated soft mineral deposits. They differ from lithosols in that they are usually not stony. They are largely confined to areas of sand dunes, loess, and steeply sloping glacial drift.

Alluvial soils are of much greater agricultural importance than the azonal soils already mentioned. Large areas are found along rivers such as the Mississippi and Ohio wherever recent alluvium occurs. Valley bottoms in humid regions commonly contain alluvial soils. When properly

drained such soils are very productive. The rich lands of the Misssisippi delta and floodplain are good examples.

12:19. THE SUBDIVISION OF A SOIL GROUP—SOIL SERIES

The first concept in soil classification is a comprehensive one—the decision as to whether a soil is *zonal, intrazonal,* or *azonal* and to what great *soil group* it belongs. These groups already have been discussed, but in passing it is well to emphasize again that a soil group is a very broad subdivision based on the recognized tendency of soils under a given set of conditions to assume a general similarity as to profile and other characteristics. And, as may be expected, there are many varieties of soils within each great group. The reasons are not difficult to discover.

In the United States, as elsewhere, many of the soils are young and the original geological characteristics of the parent materials are much in evidence. Again topography is variable and with the accompanying dissimilarities in depth, drainage, aeration, organic accumulation, and the like, a heterogeneity of profile is induced. (See Fig. 12:8.) Thus, even if climate were uniform, a great miscellany of soils would still occur within any particular region. Indeed the layman is likely to be impressed by the unlikenesses within a great soil group rather than by the similarities that make it possible to establish such a broad division.

Soil series defined. Obviously then, the next step is a subdivision within each great soil group. This is necessary if any detailed study is contemplated or any agricultural evaluation is to be made. This separation is accomplished by subdividing the great soil groups into lesser groups called *series*. These units are quite distinct. The soils of any one series have similar profile characteristics except for the texture of the surface layer. In more precise terms, a *series* is a group of soils developed from the same kind of parent material, by the same genetic combination of processes, and whose horizons are quite similar in their arrangement and general characteristics. Except for the texture of the A horizon, and this is a very important reservation, these characteristics are more or less identical.

Differentiating and naming of series. In field work a more or less standard profile is finally set up for each series and all soils that approach it closely enough are made a part of this particular subdivision. Ideally, the only differences of agricultural importance that should exist between the various soils of any given series are in the textures of the surface layer and even here the range should not be great.

Series are of course established on the basis of profile characteristics. This requires a careful study of the various horizons as to number, order, thickness, texture, structure, color, organic content, and reaction (acid, neutral, or alkaline). Such features as hardpan at a certain distance below the surface, a distinct zone of calcium carbonate accumulation at a certain depth, or striking color characteristics greatly aid in series identification.

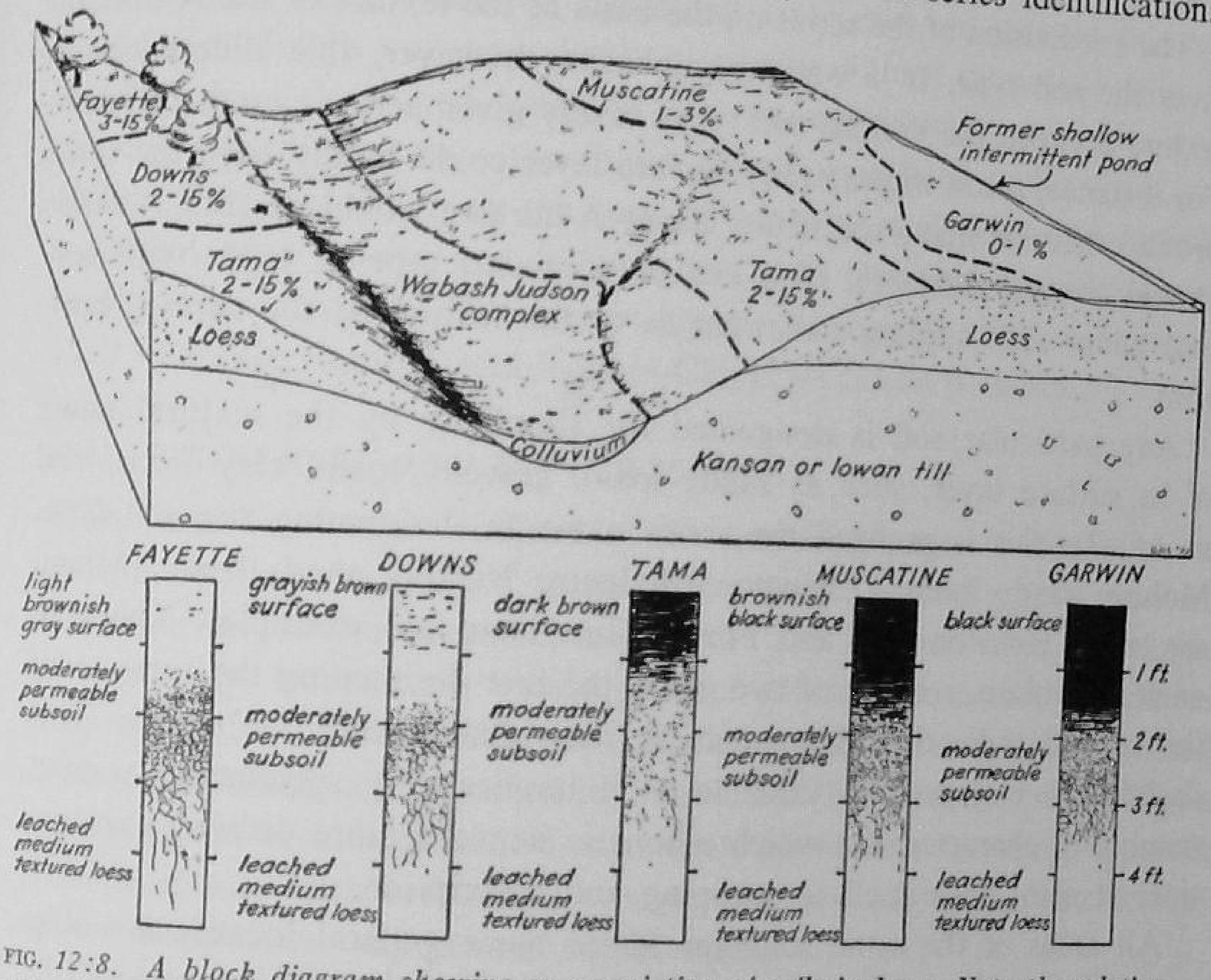

FIG. 12:8. *A block diagram showing an association of soils in Iowa. Note the relationship of soil type to (1) parent material, (2) vegetation, (3) topography, and (4) drainage. In this diagram two gray-brown podzolic soils (Fayette and Downs), two prairie soils (Tama and Muscatine), and a hydromorphic soil, or Wiesenboden (Garwin) are shown. (From Riecken, F. F., and Guy D. Smith, "Principal Upland Soils of Iowa, Their Occurrence and Important Properties,"* Iowa Agr. Exp. Sta. Agron. 49, Revised.)

In the United States each series is given a name, usually from some city, village, river, or county, such as Fargo, Muscatine, Cecil, Mohave, Ontario, and the like. Series names should be common, simple, and easy to spell.

It is well to state at this point that similar series are grouped together to give soil families.[30] Thus, the classification so far runs as follows: (1) the

[30] The family grouping is not as yet well worked out and is of interest only to the specialist.

order, that is, whether zonal, intrazonal, or azonal; (2) the *suborder,* such as light-colored soils of the arid regions; (3) the *group,* as, for example, the gray-brown podzolic or chernozem; (4) the *family,* and finally (5) the *series* just considered.

12:20. SOIL TYPES, PHASES AND CATENAS

The subdivision of the series on the basis of the texture of the A horizon gives the soil *type.* It is well to emphasize, however, that differences in texture between the various soil types in any given series cannot be great. For instance, a soil with a sandy surface layer could hardly have the same profile otherwise that a soil with a clayey A horizon would possess. A series should consist, therefore, of a key or dominant type or types with several minor soils varying somewhat as to the texture of the surface horizons.

Any particular soil is designated for simplicity by the textural name of its surface layer, such as sandy loam, gravelly loam, clay loam, and so on. To this is prefixed the series name in designating the soil type. Mohave sandy loam, Carrington silt loam, Norfolk sandy loam, Miami silt loam, Houston clay and Fort Collins loam are examples. The type name, therefore, consists of two parts, the first designating the series, and the second indicating the particular individual within the series. This designation is especially valuable as it implies very specifically a great number of characteristics which otherwise would require detailed explanation. It also lends itself to mapping and description.

All areas of the same soil type in the same general locality are alike (within limits) as to profile characteristics, including the texture of the surface horizon, and were originally similar in fertility. Methods of farming have, of course, developed differences in immediate productivity. This sometimes leads to confusion in comparing soils of different farms.

Areas of the same soil type at some distance from each other usually show certain minor variations. For example, Knox silt loam soils 50 or 60 miles apart exhibit certain well-recognized deviations that must be considered in making fertility recommendations. Again variations are to be expected as one soil type grades into another. Thus, the heterogeneity of the soil type as to minor characteristics must constantly be kept in mind.

Soil phase. A soil type is not quite the ultimate subdivision of a series since *phases* are often mapped within types. A *phase* is a subdivision on

the basis of some important deviation such as erosion, slope, stoniness, or soluble salt content. It really marks a departure from the normal, or key type, already established. Thus, a Cecil sandy loam, eroded phase, or a Hagerstown silt loam, stony phase, are examples of soils where distinctions are made in respect to the phase.

Soil catenas. Before proceeding with a consideration of soil survey methods, one more means of classifying associated soils should be mentioned. Zonal soils and imperfectly or poorly drained intrazonal soils, all of which have developed from the same parent materials under the same climatic conditions, are often found closely associated under field conditions. This association on the basis of drainage or of differences in relief is known as a *catena* and is very helpful in practical classification of soils in a given region. The relationship can be seen by referring to Figure 12:9 where the Bath-Mardin-Volusia-Chippewa catena is shown.

12:21. SOIL SURVEY AND ITS UTILIZATION [31]

The classification as outlined in the preceding pages is susceptible to enough detail and precision to make it valuable in soil survey. In fact, it was developed for just such a purpose. The function of a soil survey is to classify, locate on a base map, and describe the nature of soils as they occur in the field. The soils, if the system utilized in the United States is followed, are classified into *series* and *types* on the basis of their profile characteristics. The field man, since his work is localized, concerns himself mostly with series and type separations, giving the broader regional distinctions only general consideration.

Field mapping. As the series and type identification progresses in the survey of any area, the location of each individual soil is shown on a suitable base map. The maps often used in the United States are aerial base maps such as the one shown in Figure 12:10. In many respects they have considerable advantage over the ordinary contour maps in that land cover and field boundaries show very clearly. Thus, the surveyor can quickly locate his position on the map and can indicate in great detail the soil boundaries.

Using the procedure outlined above, a field map is thus obtained which not only gives the soil type and phase, but also often furnishes informa-

[31] For an authoritative discussion of soil survey procedures and related features see "Soil Survey Manual," Agricultural Handbook No. 18, by Soil Survey Staff, Bur. of Plant Industry, Soils and Agr. Engineering, Wash., D. C., 1951.

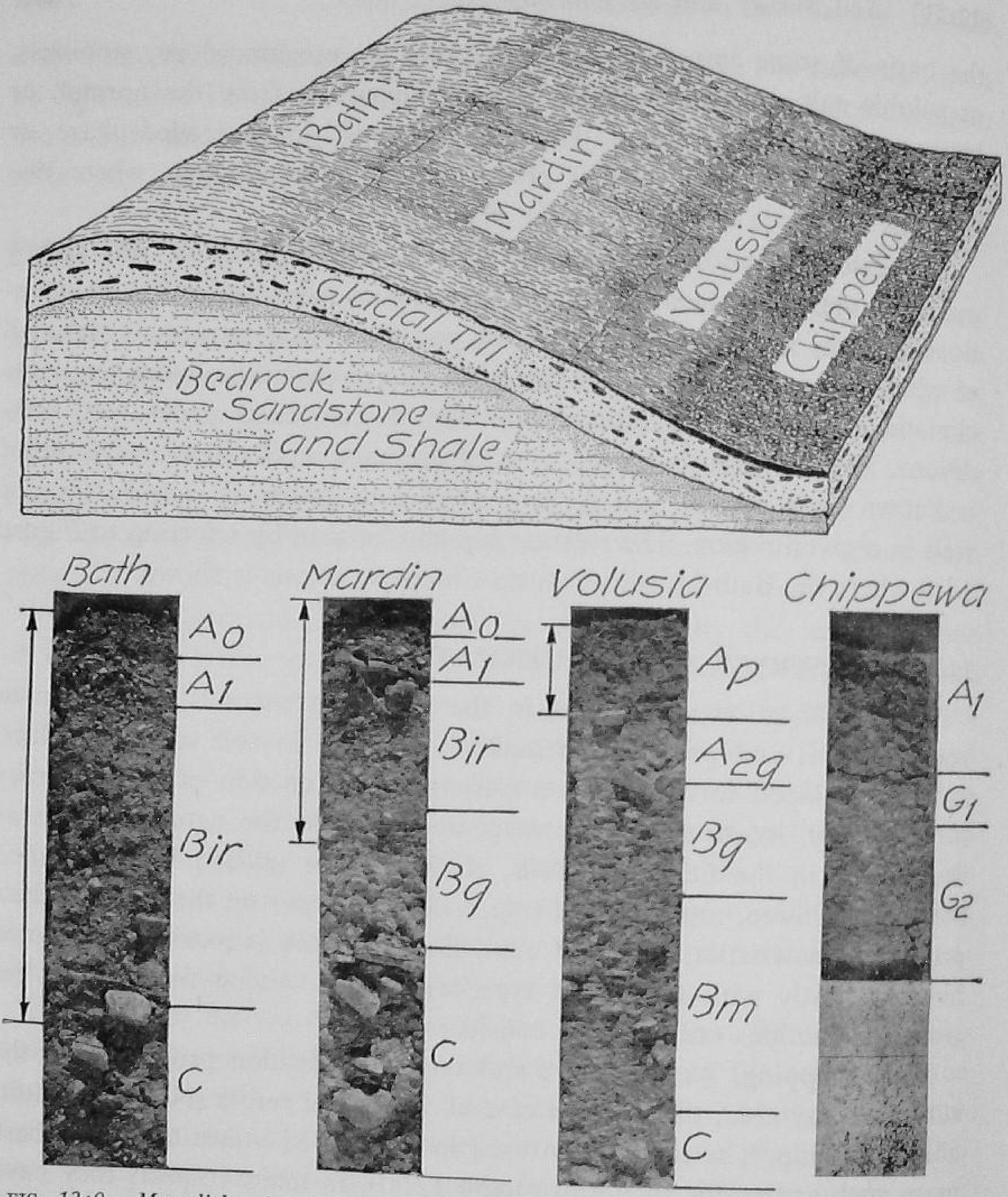

FIG. 12:9. *Monoliths showing four soils of a drainage catena (below) and a diagram showing their topographic association in the field (above). Note the decrease in the depth of the well aerated zone (indicated by arrows) from the Bath soil (left) to the Chippewa (right). The latter remains poorly aerated throughout the growing season. These soils are all developed from the same parent material, differing only in drainage and topography. The Volusia soil as pictured was cultivated (note Ap = plowed) while the others were located on virgin sites. Other symbols are as follows: ir = iron; g and G = gleyed, a mottled layer indicative of poor aeration, G being more intensely gleyed; m = massive compact layer.*

tion as to slope and severity of erosion. Thus, the map becomes of even greater practical value.

The field map, after the separations have been carefully checked and

FIG. 12:10. *An aerial photograph of an area in Boone County, Iowa. Such maps are invaluable in making soil surveys since the field man is able to visualize quickly the topographical features of the section in which he is working.*

Note the contrast between cropped areas and those in woods. The roads, farm buildings, and individual fields are plainly visible. Alternate, irregular light and dark streaks are seen where surface erosion has taken place.

The area shown is representative of the forest grassland transition zone where gray-brown podzolic (forest) soils and prairie (grassland) soils are prevalent. (U. S. Soil Conservation Service photo.)

correlated, is now ready for reproduction in color. When published it accompanies a bulletin containing a discussion of the topography, climate, agriculture, and soils of the area under consideration. Each soil type is minutely described as to profile and suggestions as to practical management are usually made. Such a field map is shown in Fig. 12:11 where the relationship of topography to soil associations can be readily seen.

Soil conservation surveys, which are simply an extension of the usual soil survey, are now common. In addition to soil type, the land use, the slope, and degree of erosion are shown. Colors and suitable symbols are employed to indicate on one map the various factors. Since such a survey is often carried out with the farm as the unit area, the scale of the base map in such cases is likely to be greater than the usual 1-inch-to-the-mile basis. On the other hand, when the agricultural value of the land is low, a more general survey, called a *reconnaissance,* is made. Here much of the usual detail is omitted.

Use of soil surveys. Soil-survey bulletins and maps perhaps attain their greatest usefulness as a basis for other scientific work. Profile studies, whether physical, chemical, or biological, must be preceded by some sort of a survey or classification. Crop research of all kinds is facilitated if a soil survey has previously been made. Land evaluation and appraisal, statistical studies, and sociological investigations are other interests served. Perhaps the soil survey in a technical way is of greatest value in land classification and erosion control. These two phases probably justify the time and money spent in the United States on this work.

In a more practical way the extension specialist and the county agricultural agent find the survey maps and bulletins a guide in making suggestions and recommendations. They afford information that it would be impossible to obtain elsewhere, and for a broad, over-all concept of an area nothing better can be consulted. In some cases simpler and more practical bulletins follow the rather technical ones. Opportunity is thus given for the effective presentation of information and up-to-date recommendations that cannot be included in the soil-survey bulletin itself.

The value of an illustrative means of showing the relationships among soil types within a given region can be seen by referring to Figure 12:8. A glance at this diagram shows the meaning and need for classification. It also suggests that soil management must be accommodated to the soil type insofar as possible.

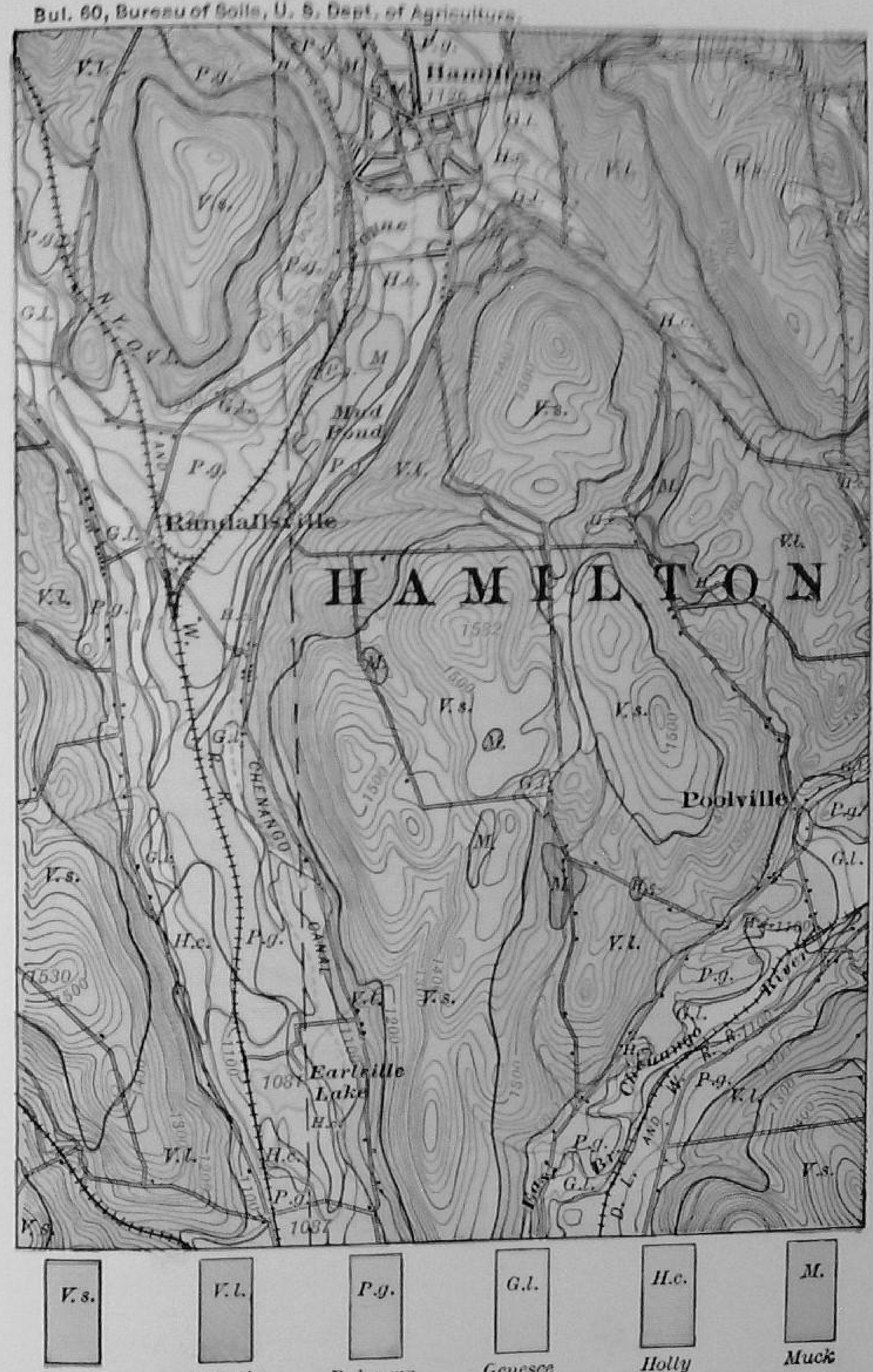

FIG. 12:11. *Part of the Madison County, New York, soil map showing the topography and drainage and the relation of the various soil types to one another. The Volusia series has been formed from ground moraine, the Palmyra from glacial outwash, while the Genessee and Holly are alluvial. Note the varying elevations of the peat (called muck) deposits.*

BLOCK DEVELOPMENT OFFICE. * T. KALLUPATTI *

CHAPTER

13 Organic Soils—Nature, Properties, and Utilization

ON THE basis of organic content two general groups of soils are commonly recognized—mineral and organic. (See Section 1:5, page 7.) The so-called mineral soils vary in organic matter from a mere trace to as high as 15 or even 20 per cent. Those soils, the organic content of which ranges from 20 or 25 to as high in some cases as 90 or 95 per cent, are arbitrarily termed organic soils. For those that are cultivated, perhaps 80 per cent of organic matter is a good average figure.

Organic soils are by no means so extensive as are mineral soils, yet their acreage in the aggregate is quite large, especially in certain regions. Their use in favored localities for the intensive production of crops, particularly vegetables, has become so important as to attract considerable popular notice. As the development of such lands goes on, more and more attention will be given to their investigation. In the past organic soils have not received the study that they deserve. As a result, less exact knowledge regarding their physical, chemical, and biological characteristics is available than for mineral soils. In general, however, the same edaphological principles hold in a broad way for both.

13:1. GENESIS OF ORGANIC DEPOSITS

Marshes, bogs, and swamps provide conditions suitable for the accumulation of organic deposits. The highly favorable environment in and adjacent to such areas has encouraged the growth of many plants, such as pondweed, cattails, sedges, reeds and other grasses, mosses, shrubs, and also trees. These plants in numberless generations thrive, die, and sink down to be covered by the water in which they grew. The water shuts out the

air, prohibits rapid oxidation, and thus acts as a partial preservative. The decay that does go on is largely through the agency of fungi, anaerobic bacteria, algae, and certain types of microscopic aquatic animals. They break down the organic tissue, liberate gaseous constituents, and aid in the synthesis of humus.

As the process continues, the organic mass becomes brown or even black in color. If decomposition proceeds far enough, this mass of organic soil-material acquires such profile characteristics as to justify its designation as a true organic soil. Apparently the humus now present is the result of ligno-protein unions and polyuronide formation much like the processes prevalent in mineral soils. (See page 158.)

The layering of peat beds. As one generation of plants follows another, layer after layer of organic residue is deposited in the swamp or marsh. The constitution of these successive layers changes as time goes on since a sequence of different plant life is likely to occur. Thus, deep-water plants may be supplanted by reeds and sedges, these by various mosses, and these in turn by shrubs, until finally forest trees, either hardwoods or conifers, with their characteristic undergrowth, may gain a foothold. The succession is by no means regular, or definite, as a slight change in climate or water level may alter the sequence entirely.

The profile of an organic deposit is, therefore, characterized by layers, differing not only as to their degree of decomposition but also as to the nature of the original plant tissue. In fact, these layers later may have become soil horizons. Their final character is determined in part by the nature of the original materials and in part by the type and degree of decomposition. Thus, the profile characteristics of organic soils, as with those dominantly mineral in nature, are in part inherited and in part acquired.

13:2. AREA AND DISTRIBUTION OF PEAT ACCUMULATIONS

As might be expected, peat deposits are found all over the world wherever the conditions are favorable. But only in certain countries are these accumulations utilized in any intensive way. In Germany, Holland, Norway, Sweden, Russia, Poland, Ireland, England, and Scotland, economic use has long been made of peat and peat products. Organic deposits in Germany occupy perhaps 5,000,000 acres, in Sweden 12,000,000 and in Ireland 3,000,000 acres. Canada possesses approximately 12,000,000 acres of peat, mostly undeveloped.

In non-glaciated United States. Organic deposits of the nature described occur in many parts of the United States.[1] In Florida the Everglades, spread out over an extensive plain, contain considerably over 2,000,000 acres of saw-grass (sedge) accumulations. Along the Atlantic coastal plain great marsh deposits are found, especially in North Carolina. In California there are the tule-reed beds of the great central valley, approximately 300,000 acres in extent. Louisiana alone possesses about 3,000,000 acres of organic accumulations of various kinds. All of these are southward and outside of the glaciated areas of the United States. They are related only indirectly to the glaciation through a change in climate and a rise in ocean level due to the melting of the continental ice sheet.

In glaciated United States. Northward in the regions covered by glacial debris of various kinds, organic deposits are even more extended. In fact, about 75 per cent of the peat deposits of continental United States occur in the glaciated areas. Minnesota, Wisconsin, and Michigan are especially favored in this respect, their combined acreage running well above 12,000,000 acres. Washington, with about 2,000,000 acres, ranks highest of all the western states. Indiana, Massachusetts, New York, and New Jersey fall into the 300,000- to 500,000-acre class. Other states, especially Iowa, Illinois and Maine, contain smaller but often very important areas.

The total acreage of peat deposits in the United States proper is in the neighborhood of 25,000,000 acres. In Alaska and northern Canada, and in northern Asia and Europe as well, there occur great areas of peat derived from sedges and mosses called *muskeg*. In many cases the subhorizons of such accumulations are perpetually frozen. They are an important feature of the tundra soils that characterize these regions. (See page 336.)

The Pleistocene glaciation by impeding drainage led to the formation of swamps and bogs. As the climate became milder and gradually attained its present status, conditions were ideal for swamp vegetation to flourish. As a result, certain parts of the glaciated region are liberally dotted with

[1] For tabular information as to acreages see Gustafson, A. F., *Soils and Soil Management*, McGraw-Hill Book Company, Inc., New York, 1941, p. 395.

Many of the states possessing economically important peat areas have published bulletins regarding the area, quality, and agricultural utilization of the deposits. Articles dealing with peat also will be found in the *Agronomy Journal (Journal of the American Society of Agronomy)*, *Soil Science*, and the *Proceedings of the Soil Science Society of America.*

organic accumulations ranging from a few inches to 50 or even 100 or more feet in depth. Some areas, a number of square miles in extent, are solidly occupied as in Minnesota, while in other localities the peat lies in isolated patches or in long ribbons as in southeastern Wisconsin and in central New York. Both of the latter accumulations are in many cases associated with drumlins. (See page 315.) These long cigar-shaped hills when parallel often alternate with narrow swamps several miles in length that are filled with organic matter in various stages of decay.

13:3. CLASSIFICATION OF PEAT— DESCRIPTION OF THE VARIOUS TYPES

Peat, regardless of its stage of decomposition, may conveniently be classified according to its parent materials and under three general heads as follows:

Classification of Peats [2]

1. Sedimentary peat (usually rubbery)	mixtures of water lilies, pondweed, hornwort, pollen, plankton, etc.	
2. Fibrous peat	sedges of various kinds, mosses—sphagnum, hypnum, and others, reeds and other grasses, cattails, both latifolia and angustifolia	and their mixtures
3. Woody peat	deciduous and coniferous trees	and their undergrowth

Sedimentary peat. Sedimentary peat usually accumulates in comparatively deep water and, therefore, generally is found well down in the profile. Sometimes, however, it is intermixed with the other types of peat.

[2] In Germany peats are classified in a general way into *high-moor* and *low-moor* in reference to the shape of the deposits. The high-moors are convex, that is, raised in the center, while the low-moors are concave. The former is usually quite acid and low in calcium, the latter less acid and quite high in exchangeable calcium.

In England the corresponding terms are *moor* and *fen*. The term *heathland* refers to a shallow acid peat.

For a discussion of American peats and their classification, see Dachnowski-Stokes, A. P., and V. Auer, "American Peat Deposits," *Handbuch der Moorkunde*, Gebrüder Borntraeger, Berlin, 1933, Band 7.

Sedimentary peat seems to be derived from plant materials that humify rather freely and rather completely. Due to the nature of the original tissue and perhaps also to the type of decay, a highly colloidal and characteristically compact and *rubbery* substance develops. This material is unique and so different from the other types of peat commonly found in the profile that it always attracts considerable attention when encountered.

Not only is sedimentary peat rubbery in character but it is usually olive-green in color when in its natural position. On exposure to the atmospheric air it darkens rapidly, sometimes becoming almost black. Due to its highly colloidal nature, its moisture capacity is high, perhaps four or five times its dry weight. Water thus imbibed is held tenaciously and therefore this peat dries out very slowly. The colloidal materials of sedimentary peat are largely irreversible. Consequently, when once dry, this peat absorbs water very slowly and persistently remains in a *hard* and *lumpy* condition.

Sedimentary peat is thus very undesirable as a soil, because its unfavorable physical condition renders it unsatisfactory for use in the growing of plants. Even small amounts in the furrow-slice lower the desirability of the peat for agricultural purposes. Fortunately, in most cases, it occurs well down in the profile and ordinarily does not appear above the plowline. Therefore, its presence usually is unnoticed or ignored unless it obstructs drainage or otherwise interferes with the agricultural utilization of the peat deposit.

Fibrous peats. As indicated by the classification just presented, a number of fibrous peats occur, often in the same swamp deposit. They are all heterogeneous in character, high in water-holding capacity, and may exhibit varying degrees of decomposition. They differ among themselves especially as to their filamentous or fibrous physical nature. Undecomposed moss and sedge are fine enough to be used in greenhouses and nurseries and as a source of organic matter for gardens and flower beds. Reed and cattails, however, are somewhat coarse, especially the latter. In fact, the cattail accumulations are of little value unless well decomposed. Fortunately their area is not large.

All of the fibrous materials as they decay make satisfactory field soils, the cattail soil perhaps being the least desirable, the sedge or moss usually receiving a preferred rating. Fibrous peats may occur at the surface of the organic accumulation of which they are a part or well down in the profile. They usually lie above the sedimentary deposit when this type of peat

is present. Nevertheless, if just the right fluctuation of conditions has occurred a stratum of the latter may lie imbedded within the fibrous-peat horizons and rather near the surface.

Woody peat. Since trees are the climax vegetation in many swamp deposits, woody peat is usually at the surface of the organic accumulation. This is not an invariable rule, however, since a rise in water level might kill the trees and so favor reed, sedge, or cattail as to give a layer of fibrous material over the woody accumulation. It is not particularly surprising, therefore, to find subhorizon layers of woody peat.

Woody peat is brown or black in color when wet, according to the degree of humification. It is loose and open when dry or merely moist, and decidedly nonfibrous in character. Virgin deposits often are notably granular. It is thus easily distinguished from the other two types of peat unless the samples are unusually well disintegrated and decomposed.

Woody peat develops from the residues not only of deciduous and coniferous trees but also from the shrubs and other plants that occupy the forest floor of the swamp. Maple, elm, tamarack, hemlock, spruce, cedar, pine, and other trees occur as the climax vegetation in swamps of temperate regions. In spite of the great number of plants that contribute to its accumulation, woody peat is rather homogeneous unless it contains admixtures of fibrous materials. Such heterogeneity occurs more commonly than is generally supposed.

The water capacity of woody peat is lower than that of fibrous peats, especially those formed from mosses and sedges. For that reason woody peat is less desirable than these peats for use in greenhouses and nurseries where such materials are used as a means of moisture control and a compost conditioner. Woody residues produce a field soil, however, that is quite superior and much prized for the growing of vegetables and other crops. Such woody peats, unfortunately, are confined in general to Wisconsin, Michigan and New York.

13:4. VARIOUS USES OF PEAT[3]

Nurseries, greenhouses, and lawns. Peat is utilized in a number of ways, depending on the nature of the material. In the United States, Canada,

[3] Feustel, Irvin C., "The Present Status of Research Relating to the Use of Peat and Muck as Soil Amendments," *Proc. Soil Sci. Soc. Amer.*, 4: 271–274, 1939. This article carries an excellent bibliography.

Waksman, S. A., and H. B. Schulhoff, "The Nature and Properties of Peats in New Jersey," *Soil Sci.*, 54: 447–461, 1942.

and Europe the more or less undecomposed products are very commonly employed as a source of organic matter. This is true of moss and sedge peat. When incorporated with mineral soil in sufficient quantities, peat not only insures a good physical condition but markedly increases the water capacity of the mixture. Soils for potting and other purposes are greatly benefited physically by its use. It is thus valuable in greenhouses, gardens, flower beds, and nurseries both as a soil amendment and as a mulch around growing plants of all kinds.

Peat is likewise useful in the preparation of lawn soils, of golf greens, and in numerous other ways where tilth and organic matter are important factors. While the undecayed materials are generally utilized for such purposes, the humified products are on occasion also employed. They are often just as satisfactory and in some instances even superior to the less decayed types.

As bedding, litter, and packing. Peat, especially the sedge and moss types, may be used in stables as bedding and litter. Such material readily absorbs and conserves the liquid manure, and when the mixture is applied to the soil, the peat contributes a considerable amount of slowly decomposing organic matter. However, the presence of the liquid and solid manure activates the organic matter of the peat and renders its decomposition more rapid than otherwise would be the case. Peat is likewise utilized in poultry houses as a litter under the roosts and in the runways. Sphagnum and other suitable forms of fibrous peats even serve as packing materials in place of excelsior and the other substances commonly employed. They also are good insulating materials.

As fuel. In Holland, Germany, Belgium, Ireland, and other countries of Europe, peat is dug out in brickette form, dried thoroughly, and used as fuel. Thus, vast amounts of Dutch and German peat have not only been used locally, but also were shipped considerable distances for industrial purposes. In lands where wood is scarce and coal expensive, peat deposits are an exceedingly valuable natural resource. In Holland the excavation of peat has been so regulated as to leave the site well drained and in such a condition that field crops can be grown, aided by the portions

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Peterson, J. B., "Characteristics of Iowa Peat Profiles," *Proc. Soil Sci. Soc. Amer.*, 9: 126–130, 1944.

Albert, A. R., "Status of Organic Soil Use in Wisconsin," *Proc. Soil Sci. Soc. Amer.*, 10: 275–278, 1945.

Jones, L. A., *et al. Soils, Geology and Water Control in the Everglades Region,* Bul. 442, Univ. Florida Agr. Exp. Sta., 1948.

of the organic matter that, by law, must be left behind. Some of the most productive agricultural areas in Holland lie on the site of these reclaimed and properly exploited bogs. Such soils must be heavily treated, of course, with commercial fertilizer.

Field soils. In the United States the most extensive use of peat is as a field soil, especially for vegetable production, although other crops are grown, often in large acreage. Thousands of acres are now under cultivation, often producing two crops a year. In some respects the vegetable industry has been revolutionized by the exceedingly favorable nature of these organic soils when adequately drained and properly fertilized. Peats for such use should be well decomposed, the decay often having gone so far as to make it almost impossible to identify with certainty the various plants that have contributed to the accumulation. As the following pages indicate, the edaphological interest in peat relates mainly to its use as a natural soil and not as an artificial and commercial product for greenhouse, nursery, or factory consumption.

However, more and more of the processed peat is appearing on the market both in Canada and the United States. Such material is mostly sedge and moss, undecomposed or only slightly decayed. With great quantities of suitable material available, there is no reason why the demand within the United States should not be met with a domestic product, rather than, as heretofore, with imports.

13:5. MUCK VERSUS PEAT—MUCK SOILS

Organic deposits are conveniently classified on the basis of the amount of organic matter that they contain. When the quantity of this constituent lies below 50 per cent and exceeds 18 or 20 per cent, the accumulation is technically designated as *muck*. When the percentage is above 50, the material is referred to as *peat*. This distinction is somewhat confused in certain parts of the United States by the use of the term muck in reference to all peats that are well enough decomposed to serve as a field soil.[4] To add to the confusion mineral soils relatively high in organic matter but whose percentage thereof is less than 20 are sometimes designated as muck. In the pages that follow the chemical distinction between peat and muck as cited above will be adhered to.

[4] Crop specialists as well as farmers often use the terms *peat* and *muck* in reference to the state of decomposition of the organic matter, peat referring to the slightly or nondecayed deposits and muck to those materials markedly decomposed. This further adds to the confusion of the terminology.

When the organic matter of muck is well decomposed, this material makes a very satisfactory soil. The large content of mineral matter, 50 per cent or more, is usually due to an inwash of sand and silt. Fringes and tongues of muck are therefore common around the edges of peat deposits, especially if conditions of rainfall and topography are favorable for erosion. One of the best known areas of true muck occurs on the southern and eastern shores of Lake Okeechobee in Florida. It is locally known as custard-apple land. While muck may be used successfully for the production of vegetables and other crops, peat soils are far greater in extent and agriculturally are much more important. Peat soils for this reason will receive the major attention in the discussion that follows.

13:6. PEAT SOILS—THEIR CLASSIFICATION AND PROFILE SEQUENCE

Since the parent materials influence so definitely the physical and chemical properties of the resultant peat soils, any classification must take these original substances into account. The following grouping is simple and, to anyone familiar with peat soils, very convenient as well. Since sedimentary peat is seldom near the surface on good peat land, and when so located is physically very undesirable, it is not included in the peat soil classification presented below:

Classification of Peat Soils
Based on Parent Materials

Fibrous peat soils	(1) sedges of various kinds (2) mosses—sphagnum, hypnum and others (3) reeds and other grasses (4) cattails—latifolia and angustifolia	(5) and their mixtures
Woody peat soils	(1) deciduous and (2) coniferous trees and (3) undergrowth. In some cases, unfortunately, woody peats sometimes carry an admixture of rubbery material.	

Inherited vs. acquired characteristics. It is to be especially noted that the classification of peat soils is almost identical with the grouping of the original soil materials. (See page 368.) This is because the parent substances so definitely determine the nature of the profile that no other scheme of classification is nearly so satisfactory. With mineral soils the situation is quite different. Although parent materials are very important, the profile characteristics of a well-developed zonal mineral soil are a reflection

in large degree of climate. In other words, *acquired* characteristics rather than those *inherited* from the original materials dominate the profile (page 324). The contrast presented by peat soils is noteworthy and of great practical significance.

It was found in the consideration of mineral soils that their genesis, their outstanding characteristics, and their plant relationship could not be clearly understood without some knowledge of their profiles. The same is true of peat soils. The next logical step, therefore, is to inquire into the profile sequence of organic soils.

Peat profiles. Ideally, one might expect that the profile succession of peat soils would be rather definite for any region and especially for any particular bog. Actually, no regular sequence is found, due in large part to the irregular and uncoordinated fluctuations in the water levels of the swamps and bogs. In Michigan, Wisconsin and central New York, for instance, sedimentary peat theoretically should be near the bottom of the profile, fibrous material of some kind should come next with woody peat, if the climax vegetation is attained, at the surface. (See Fig. 13:1.) But if there has been radical changes in the water table, the succession ultimately attained might in no way resemble the ideal. Thus, woody peat is sometimes found below the surface of accumulation, covered by deposits that ideally should be encountered beneath. Admixing of the layers may further obscure the sequence. Hence, it sometimes is difficult to forecast, except in a broad way, the horizon order of the peat soils of any particular bog.

Again the profile may be immature, the possible succession of plants and their resultant accumulation having only well begun. Thus in New York, Michigan, and Wisconsin, the climax vegetation, as already suggested, is forest. Yet the surface peat in many beds may be derived from the decomposition of mosses or sedges or cattail or their intermixture, with a limited sequence or even no other organic horizons below. In fact, so variable is the arrangement of the profile layers that every peat bed requires separate investigation. As a result, Figures 13:1 and 13:2 only suggest in a tentative way what actually may be encountered under field conditions.

13:7. PHYSICAL CHARACTERISTICS OF FIELD PEAT SOILS

In spite of the many kinds of peat soils that are encountered in various parts of the United States, a generalized description will be ventured in

respect to their outstanding physical characteristics. Such statements will apply merely to that portion of the organic accumulation that normally occurs in the furrow-slice of cultivated peats. This layer determines in

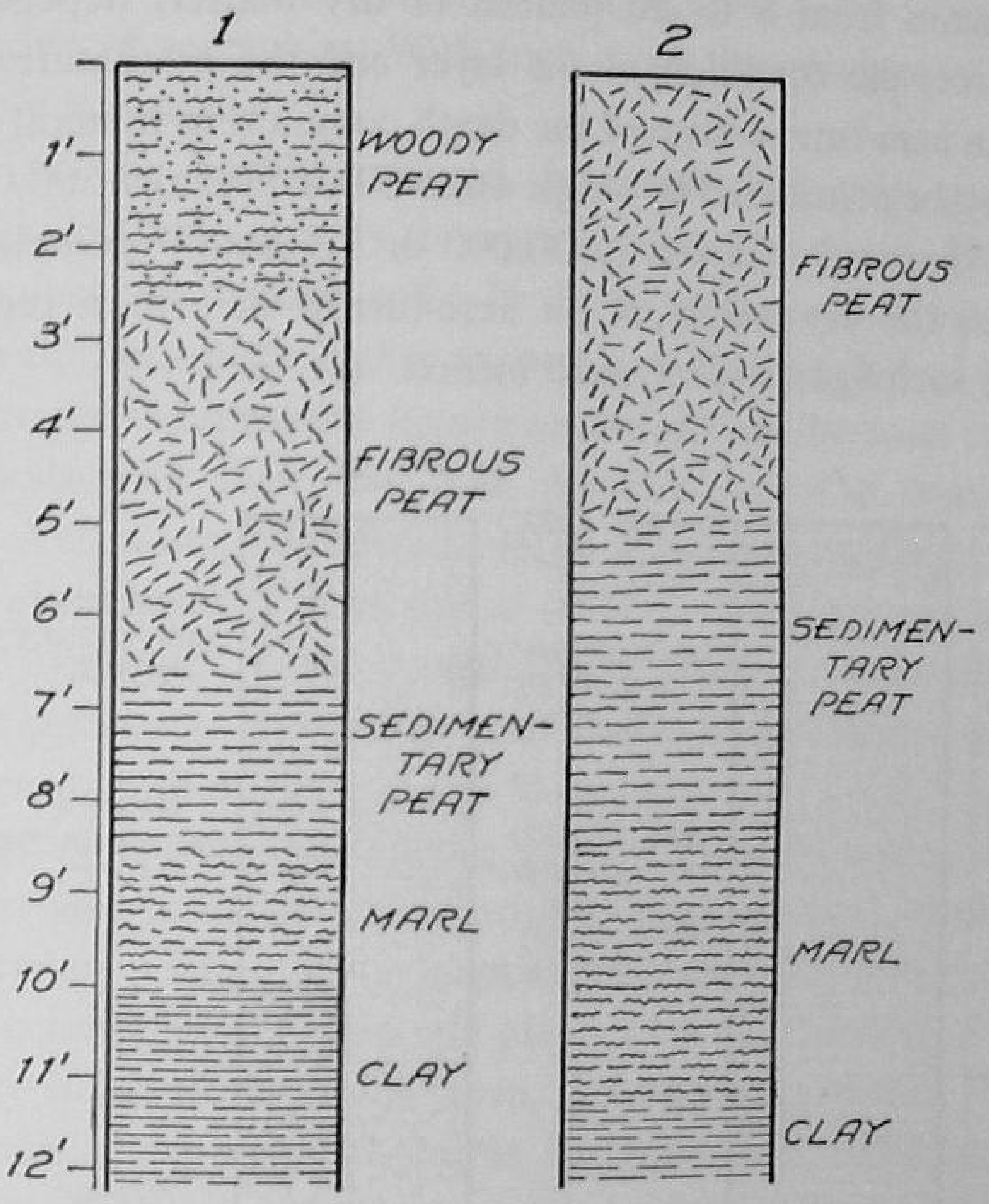

FIG. 13:1. *Representative profiles of woody peat soil (1) and a fibrous peat soil (2). The woody peat is, of course, the more desirable as a field soil. Note the presence in both profiles of rubbery sedimentary peat and of marl. (After Wilson and Staker.)*

part the suitability of the deposits for successful crop production. For a view of peat under cropping see Figure 13:3.

Color. The color of a typical cultivated peat soil, dark brown or intensely black when it is wet, is perhaps the first physical characteristic that attracts the attention. Although the original materials may be gray, brown, or reddish-brown, dark-colored humic compounds appear as decomposition advances. In general, the changes that the organic matter undergoes seem to be somewhat similar to those occurring to the organic residues of mineral soils in spite of the restricted aeration of the peat.

Bulk density. The second outstanding characteristic that is likely to be noted is the light weight of the representative peat soil when dry. The bulk

density (volume weight) compared with mineral surface soils is surprisingly low, 0.20 to 0.30 perhaps being a fair estimate. A cultivated surface mineral soil will usually fall within the limits of 1.25 to 1.45. A cubic foot of peat soil will contain from 8 to 20 pounds of dry matter, depending on its original source, the condition of the layer and the admixture of mineral materials. An acre-furrow-slice of the depth common in mineral soils, while variable, may be considered to weigh 400,000 or perhaps 500,000 pounds when dry. Compared with the 2,000,000 or 2,500,000 pounds ordinarily considered as the dry weight of an acre-furrow-slice of a representative mineral soil, such figures seem small indeed.

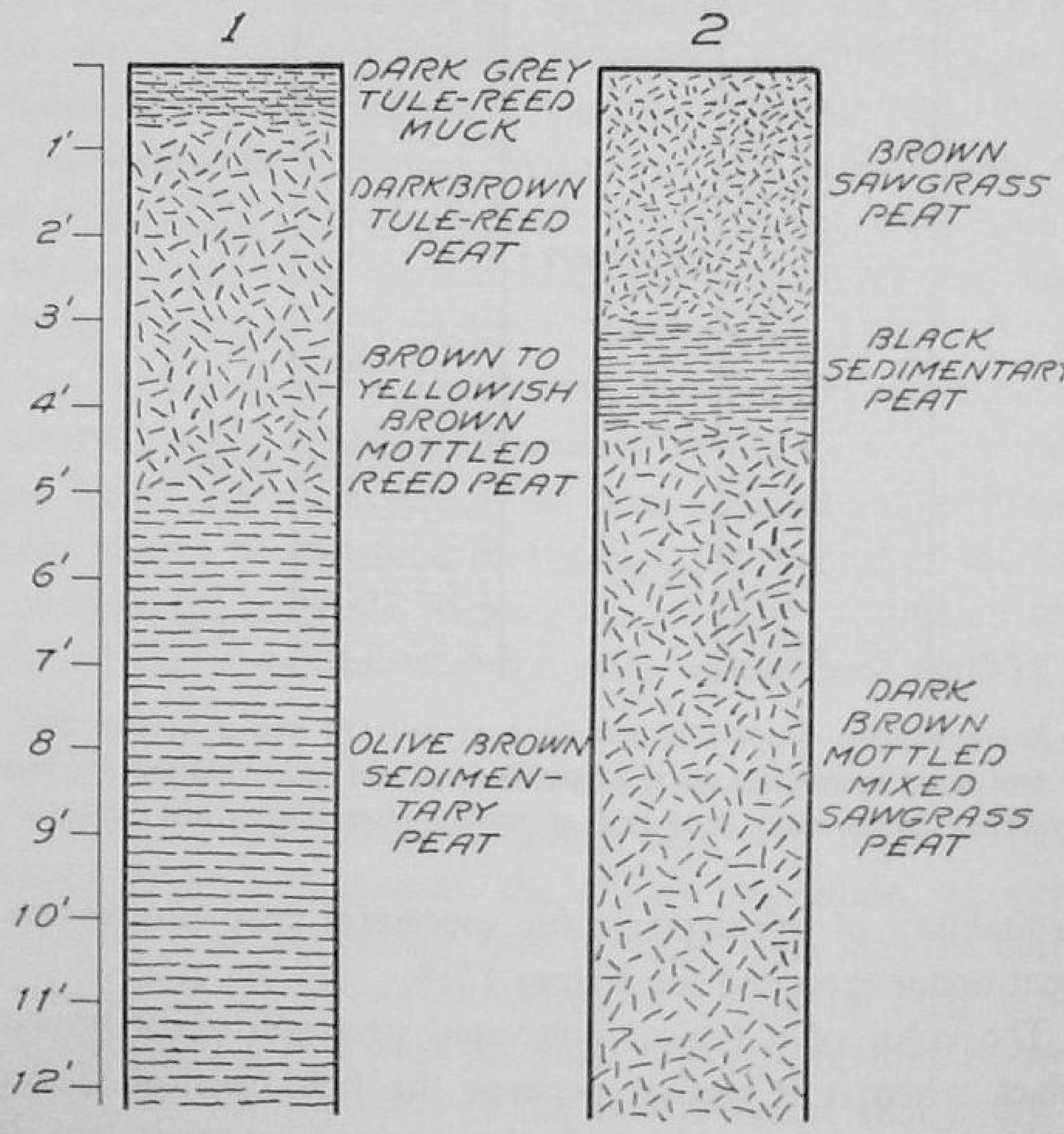

FIG. 13:2. *Generalized profiles of (1) San Joaquin tule-reed peat soil of the Mandeville type and (2) Florida saw-grass peat soil of the Okeelanta type. (After Dacknowski-Stokes' description.)*

Water capacity. A third important property of peat soil is its high water-holding capacity, one of the characteristics of highly colloidal solids and especially developed by organic matter in such a state. While a dry mineral

soil will adsorb and hold from one-fifth to two-fifths its weight of water, a peat soil will retain two or perhaps three or four times its dry weight of moisture, depending on conditions.[5] This water-holding capacity, possibly ten times greater by weight than that of mineral soils, is very important in the growing of vegetables. With such crops the presence of an abundant water supply is essential.

It must not be hastily assumed, however, that peats greatly surpass mineral soils in their capacity to supply plants with water. Two conditions militate against the organic soils. In the first place, their amounts of unavailable water are much higher proportionately than that of mineral soils. Again, since the comparative figures quoted are on the basis of dry weight, the peat soils with their low bulk densities are at a considerable disadvantage. Yet, when considered on the volume basis, the only fair comparison, a given layer of peat soil at optimum moisture will supply somewhat more water to plants comparatively than a representative mineral soil also at optimum. But not in such excess as the figures quoted in the preceding paragraph might lead one to expect.

Structure. A fourth outstanding characteristic of a typical woody or fibrous peat soil is its almost invariably good physical condition. While decayed organic matter is, in large degree, colloidal and possesses high adsorptive powers, its cohesion and plasticity are rather low. A peat soil of good quality is therefore porous, open, and easy to cultivate. These characteristics make it especially desirable for vegetable production. However, during dry periods, the lightness and looseness of peat, especially if its original granular condition has been reduced by cultivation, may lead to serious trouble, since it may drift badly in a high wind and extensive crop damage may result. It may also become ignited when dry and support a smoldering fire to such an extent as greatly to decrease or even destroy its usefulness. Such a fire often is difficult to put out and may continue for several years.

In suggesting that the surface layer of an arable peat soil is likely to be granular, it is not to be inferred that the whole profile is in this structural condition also. Far from it. All sorts of physical arrangements are encountered in the subhorizons, such as laminated, vertical, fragmental, fibrous, and rubbery. The variability from horizon to horizon is determined

[5] Undecayed or only slightly decomposed moss or sedge peat in contrast with their soils have a much greater water-holding capacity. Not uncommonly such materials can hold water to the extent of twelve, fifteen, or even twenty times their dry weight. This explains in part their value in green house and nursery operations.

not only by the character of the original materials, but also by the nature and degree of decomposition.

13:8. THE COLLOIDAL NATURE OF PEAT SOILS [6]

Because of the very high content of organic matter and the particular type of humification that occurs, the colloidality of peat soils is strikingly beyond that exhibited by most mineral soil colloids. Their interface exceeds even that of montmorillonite clay perhaps two, three, or even four times, and cation-exchange capacities are correspondingly greater. However, in spite of differences as to original tissue and conditions of genesis, the humus of peat soils greatly resembles that of mineral soils except for the intensity of the colloidal properties. For instance, it has been suggested that the cation-exchange capacity of a mineral soil is enhanced approximately 2 milliequivalents for every gram increase in humus (page 109). The figure for peat soils, especially if they are woody in origin, is somewhat higher in general, perhaps in the neighborhood of 3 milliequivalents for every gram of dry organic matter.

Formula and calcium content. Not only can the same graphic formula employed for mineral soils— Ca / H / B [Micelle] —be used to represent the colloidal complex of peat, but it is noteworthy that the same metallic cations are adsorbed by the two types of soil, and in the same order of magnitude, namely, Ca > Mg > K or Na. (See page 83.) This important difference is to be noted, however. The amount of adsorbed calcium is very much greater than is the case with mineral soils. That this is likely to be true, whether the peat is comparatively low lime or high lime, is apparent from the data of Table 13:1. The two soils in question are New

[6] Baver, L. D., "The Nature of Soil Buffering Action," *Jour. Amer. Soc. Agron.*, 23: 587–605, 1931.

Powers, W. L., "Characteristics of Dispersable Organic Colloids in Peats," *Jour. Agr. Res.*, 44: 97–111, 1932.

Muller, J. F., "Some Observations on Base-Exchange in Organic Materials," *Soil Sci.*, 35: 229–237, 1933.

Anderson, M. S., and H. J. Byers, *Character and Behavior of Organic Soil Colloids*, Technical Bulletin 377, U. S. Dept. of Agriculture, 1933.

Wilson, B. D., and M. J. Plice, *The Buffer Capacity of Peat Soils*, Memoir 146, Cornell Univ. Agr. Exp. Sta., 1933.

Millar, H. C., F. B. Smith, and P. E. Brown, "The Base Exchange Capacity of Decomposing Organic Matter," *Jour. Amer. Soc. Agron.*, 28: 753–766, 1936.

Fuestal, I. C., *The Acidic Properties of Peat and Muck*, Technical Bulletin 690, U. S. Dept. of Agriculture, 1939.

York woody peats. The total calcium content of the low-lime peat is 1.40 per cent of CaO and its cation exchange capacity is 184 milliequivalents. The corresponding figures for the high-lime soil are 6.00 per cent of CaO and 265 milliequivalents cation exchange capacity.

Table 13:1. Cationic Condition of Two New York Woody-peat Soils—One Low and the Other High in Lime[7]

Exchange Characteristics	Ca	Mg	K	Na
Exch. metallic cations, m.e. 100 gms.:				
Low-lime peat	39.8	9.7	.87	.80
High-lime peat	159.7	12.0	1.16	.87
Percentage of each cation in exchangeable condition:				
Low-lime peat	80	100	34	...
High-lime peat	75	51	27	...

The data of Table 13:1 show that most of the calcium present in peat soils and a very large proportion of the magnesium are in an exchangeable condition. Moreover, approximately one-third of the total potassium is exchangeable. All this is strikingly in contrast with a mineral soil where usually less than 35 per cent of the calcium, less than 10 per cent of the magnesium, and less than 1 per cent of the total potassium are exchangeable. (See Fig. 2:3, page 32.)

Strength of acids. The pH of peat soils, as with mineral soils, is controlled by the colloidal complex, its percentage base saturation being a major factor (page 113). The ratio of the metallic cations and the nature of the micelle also exert an influence, the latter being especially important. In general, the colloidal complex of peat when saturated with hydrogen will develop a lower soil pH than will acid mineral clays similarly charged. In other words, the peat complex is the stronger acid. This means that at the same percentage base saturation peats will be somewhat more acid than mineral soils. Also, a peat soil must be practically 100 per cent saturated with calcium and magnesium in order to attain neutrality or alkalinity. As already noted (page 400), humid-region mineral soils at 90 per cent base saturation, or sometimes even at 80 per cent, will show a pH of 7 or above.

Buffering. Since the buffering[8] of a soil is determined in large degree

[7] Calculated from Wilson, B. D., and E. V. Staker, *Ionic Exchange of Peat Soils*, Memoir 172, Cornell Univ. Agr. Exp. Sta., 1935.

[8] A simple explanation of soil buffering will be found on page 397 and ff.

by the magnitude of its cation exchange capacity, peat soils in general show an unusually marked resistance to a change in pH, much greater, of course, than do mineral soils. As a consequence, considerably more sulfur or lime is necessary to change the pH of a peat soil than to effect a similar modification in a mineral soil at a corresponding buffer level. However, the buffer curve obtained by plotting pH against percentage base saturation is of the same general order as that for mineral soils (page 400), except that the pH at 50 per cent base saturation is somewhat less.

Lime loss. Because of the large amount of exchangeable calcium and magnesium in representative peat soils and the marked evolution of carbon dioxide if such soils are drained and under cultivation, cation exchange is even more active than in mineral soils. As a consequence, the drainage waters from peat swamps and bogs usually not only carry large amounts of lime, but they are likely to be alkaline also. However, the loss of lime from most peat bogs is not serious, because of the high initial content of this constituent. Moreover, a rise of the water table that often occurs in the spring may tend to restore somewhat the bases carried downward during the previous season. In general, the lime content of cultivated peat soils is reduced to the point where this constituent is critical only in special cases.

Exchange data. In order that the cation exchange properties may be visualized a little more concretely, further data are offered respecting the two woody-peat surface soils already discussed, one comparatively low in lime, the other rather high. The exchange data, already quoted on page 115, for a representative humid-region mineral soil, are offered in contrast. See Table 13:2.

Table 13:2. Exchange Data for Two Woody-peat Surface Soils[9] and for a Representative Humid-region Mineral Surface Soil (Expressed in Milliequivalents per 100 Gms.)

Exchange Characteristics	*Woody Peats*		*Humid-region*[10]
	Low Lime	*High Lime*	*Mineral Soil*
Exchangeable Ca	39.8 m.e.	159.7 m.e.	6 to 9 m.e.
Other exch. bases, B	21.7 "	43.4 "	2 to 3 "
Exchangeable H	122.3 "	62.0 "	4 to 6 "
Total exch. capacity	183.8 "	265.1 "	12 to 18 "
Percentage base saturation	33.5	76.6	66.6
pH	4.0	5.1	5.6–5.8

[9] Calculated from Wilson, B. D., and E. V. Staker, *Ionic Exchange of Peat Soils*, Memoir 172, Cornell Univ. Agr. Exp. Sta., 1935.
[10] See page 115 of text.

13:9. CHEMICAL COMPOSITION OF PEAT SOILS

While peat soils are even more variable chemically than mineral soils, as the data below [11] indicate, certain outstanding and fairly constant characteristics are in evidence. In order to present these more clearly, a representative analysis of the surface layer of an arable peat soil is given (Table 13:3), but with the understanding that it is merely suggestive. The chemical analysis of the upper layer of a representative humid-region mineral soil (see page 26) is cited for comparison and contrast.

Nitrogen and organic matter. The high nitrogen and organic content of peat soils are self evident and need no further emphasis here. But there are two interrelated features in respect to these constituents that do justify further consideration. *Firstly,* peat soils have a wide carbon-nitrogen ratio,

[11] Chemical analyses of certain representative peat soils in percentage based on dry matter are shown in the following table:

Source	*Nature*	*Organic Matter*	N	P_2O_5	K_2O	CaO
Minnesota [a]	(low lime)	93.0	2.22	0.18	0.07	0.40
Minnesota [a]	(high lime)	79.8	2.78	0.24	0.10	3.35
Michigan [b]	(low lime)	77.5	2.10	0.26	. . .	0.16
Michigan [b]	(high lime)	85.1	2.08	0.25	. . .	6.80
German [c]	(low lime)	97.0	1.20	0.10	0.05	0.35
German [c]	(high lime)	90.0	2.50	0.25	0.10	4.00
Austria [d]	(low lime)	93.3	1.40	0.10	0.06	0.45
Austria [d]	(high lime)	83.8	2.10	0.18	0.13	2.38
New York [e]	(low lime)	94.2	1.26	0.15	0.10	0.60
New York [e]	(high lime)	81.5	2.56	0.19	0.28	6.51
Minnesota [a]	(low organic)	59.7	2.35	0.36	0.17	2.52
Minnesota [a]	(high organic)	94.0	1.70	0.16	0.04	0.31
Florida [f]	(sawgrass peat)	87.1	2.79	0.41	0.04	5.20
Canadian [g]	(peat soil)	74.3	2.19	0.20	0.16	. . .
Washington [h]	(woody sedge peat)	89.2	3.52	0.43	0.09	1.29

[a] Alway, F. J., *Agricultural Value and Reclamation of Minnesota Peat Soils,* Bulletin 188, Minn. Agr. Exp. Sta., 1920.
[b] McCool, M. M., and P. M. Harmer, *The Muck Soils of Michigan,* Special Bulletin 136, Mich. Agr. Exp. Sta., 1925.
[c] Fleischer, M., *Die Anlage und die Bewirtschaftung von Moorwiesen und Moorweiden,* Berlin, 1913.
[d] Zailer, V., "Die Entstehungsgeschichte der Moore in Flussgebiet des Ems," Zeitsch. f. Moorkultur und Torfverwertung, 8: 105–154, 1910.
[e] Wilson, B. D., and E. V. Staker, *The Chemical Composition of the Muck Soils of New York,* Bulletin 537, Cornell Univ. Agr. Exp. Sta., 1932.
[f] Hammer, H. E., "The Chemical Composition of Everglades Peat Soils," *Soil Sci.,* 28: 5, 1929.
[g] Rept. Can. Exp. Farms, Rept. of Chemist: 160, 1910.
[h] Fuestel, I. C., and H. G. Byers, *The Physical and Chemical Characteristics of Certain American Peat Profiles,* Technical Bulletin 214, U. S. Dept. of Agriculture, 1930.

the minimum being in the neighborhood of 20. In contrast, this equilibrium ratio for a cropped mineral soil is usually around 10 to 12.

Table 13:3. Suggested Analysis for a Representative Peat and a Mineral-surface Soil Respectively, Expressed in Per Cent Based on Dry-matter

Constituent	*Peat Surface Soil*	*Mineral Surface Soil*
Organic matter	80.00	4.00
Nitrogen (N_2)	2.50	0.15
Phosphoric acid (P_2O_5)	0.20	0.10
Potash (K_2O)	0.10	2.00
Lime (CaO)	4.00	0.60
Magnesia (MgO)	0.50	0.50
Sulfur trioxide (SO_3)	1.50	0.10

Secondly, peat soils, in spite of their wide carbon-nitrogen ratio, generally show exceedingly vigorous nitrification. In fact, the nitrate accumulation, even in a low-lime peat, is usually greater than that of a representative mineral soil. This can only be explained on the basis of the large amount of nitrogen carried by the peat, the presence of adequate calcium, and the inactivity of part of the carbon. Thus, the *effective* carbon-nitrogen ratio of peats may be as narrow as that of mineral soils. As a result, the multiplication of the competitive general-purpose heterotrophic organisms is not excessively encouraged. The nitrifiers, therefore, are given ample opportunity to oxidize the ammoniacal nitrogen.

Phosphorus and potassium. The phosphorus and potassium of peat are both low, the latter exceedingly so in comparison with a mineral soil. Even the phosphoric acid is actually less in pounds per acre-furrow-slice. On this basis, the representative mineral soil is cited as containing 2,000 pounds of P_2O_5. An equivalent layer of peat soil (say 500,000 pounds) would furnish only 1,000 pounds of P_2O_5 or one-half as much. This explains why, in the growing of crops on a peat soil, phosphorus as well as potash must be applied in large amounts.

Calcium and pH. The high calcium content of peat soils is easily explained. Much of the water entering swamps is from seepage and has had ample opportunity of dissolving lime in its passage through the subsoil and substratum of the surrounding uplands. Moreover, many swamps contain a deposit of bog lime (see page 384) or other calcareous matter in their lower profile layers. This cannot but exert an influence. Conse-

quently, the waters in which swamp and bog plants live and decay are often heavily charged with calcium acid carbonate. Since decaying organic matter is highly adsorptive and calcium ions plentiful, the resultant peat horizons cannot avoid the presence of large amounts of exchangeable calcium ions. Nor is leaching, as with mineral soils, such an important factor in robbing the surface layers of lime. High lime, most of which is exchangeable, is an outstanding characteristic of many peat soils, especially those of woody origin.

In spite of this high lime content, the majority of peat soils are distinctly acid, often very markedly so. For instance, the average pH of twelve woody-peat soils from Oswego County, New York, was 5.3 in spite of an average CaO content of 3.74 per cent.[12] So great are the cation adsorption capacities of peat soils that they may be at a low percentage base saturation and yet be carrying exceptionally large amounts of exchangeable calcium. At the same time the percentage base saturation (see page 379) is such as to assure a markedly acid condition.

Magnesium and sulfur. The percentage of magnesium in peat soil is usually no greater than that of a mineral soil. The actual amount, however, is much less due to the low dry-weight of peat by volume. (See page 376.) The situation is thus much the same as that of phosphoric acid, although it is alleviated somewhat by the high proportion of the magnesium that is held in an exchangeable condition. Peat soils, long intensively cropped, may possibly develop a magnesia deficiency unless fertilizers carrying this constituent have been used. Since most peats are seldom limed, there is little chance of adding magnesium in this particular way.

The abundance of sulfur in peat soils is not at all surprising. Plant tissue always contains considerable sulfur, and as a consequence, organic deposits such as peat should be comparatively high in this constituent. When sulfur oxidation is vigorous, as is usually the case with arable peat soils, sulfates tend to accumulate. At times a white incrustation, probably calcium sulfate (gypsum), can be observed along ditches and at other places on the surface of peat deposits where the upward movement and the evaporation of moisture is taking place. Sulfur is thus so abundant in most peat soils as to preclude any possibility of this element being a limiting factor in plant growth.

[12] Wilson, B. D., and E. V. Staker, *The Chemical Composition of the Muck Soils of New York*, Bulletin 537, Cornell Univ. Agr. Exp. Sta., 13, 1932.

Anomalous features. Peat soils in comparison with mineral soils have been shown to exhibit three somewhat anomalous features. They are worthy of restatement. *Firstly,* the representative peat soil possesses a wide carbon-nitrogen ratio and yet in spite of this it supports a very vigorous nitrification. *Secondly,* peat soils are usually comparatively high in lime and yet may be definitely acid, often highly so. And *thirdly,* in the presence of a high H-ion concentration, nitrate accumulation takes place far beyond that common in mineral soils with the same low pH. This last feature indicates that in peat soils calcium is a major factor in nitrification, and that the H-ion concentration, unless excessive, does not impede, in itself, this very important biochemical transformation.

13:10. BOG LIME—ITS IMPORTANCE

In many cases peat soils are underlain at varying depths by a soft impure calcium carbonate called *bog lime* or *marl.*[13] Its probable position in the profile is indicated by Figure 13:1. Such a deposit may come from the shells of certain of the Mollusca, which have inhabited the basin, or from aquatic plants, such as mosses, algae, and species of Chara. These organisms have the power of precipitating the calcium as insoluble calcium carbonate. It seems that these plants and animals occupied the basin before or in some cases during the formation of the peat, the marl resulting from the accumulation of their residues on the bottom of the basin or farther up in the profile.

Marl is a white or gray, soft, crumbly material, often full of shells. It effervesces freely with dilute hydrochloric acid which suggests that it is largely calcium carbonate. When the deposit is extensive enough and the presence of water or the thickness of the overburden do not interfere too much, marl may be dug out, dried and pulverized, and used as agricultural lime. In general, however, it cannot compete in price with ground limestone, although on the basis of calcium content it is often just as satisfactory a form of lime.[14]

In cases in which marl is present, it may not only supply calcium to the circulating waters, but if high in the profile, may actually become mixed with the surface peat. Thus, the exceedingly high lime content of

[13] Bog lime is usually spoken of agriculturally as *marl.* Marl, as correctly used by the geologist, refers to a calcareous clay of variable composition. Bog lime, when it contains numerous shells, is often termed *shell marl.*

[14] Bergquist, S. G., *et al., Marl—Its Formation, Excavation, and Use,* Special Bul. 224, Mich. Agr. Exp. Sta., 1932.

some organic soils may be accounted for, at least in part, on this basis. As a result, such peats are likely to be low in acidity or even alkaline. In general, an alkaline peat is not considered as highly desirable for intensive culture, especially the growing of vegetables, as are moderately acid peats.

13:11. FACTORS THAT DETERMINE THE VALUE OF PEAT SOILS

Drainage and water table. The value of peat agriculturally will depend on a number of factors. Of first consideration is the possibility of drainage, that is, a more or less permanent lowering and control of the water table sufficient to allow an adequate aeration of the root zone during the growing season. Oftentimes, however, such drainage is expensive and may require the cooperation of a number of landowners, some of whom may have no interest in the utilization of the peat.

Moreover, it may be advantageous to raise or lower the water table of peat soils at various times during the season. For instance, celery at setting is benefited by plenty of moisture. As the crop develops, the water table should be gradually lowered to accommodate the root development. The probable cost of drainage and of the seasonal control of the moisture may be such as to make the reclamation of a peat bed economically unwise. Since peat is very often covered with a forest growth, the cost of clearing also must be reckoned with. In some cases this cost may be rather high.

Depth and quality. Peat settles considerably during the first few years after drainage and cultivation have become operative, and may continue to shrink appreciably in after years.[15] If a depth adequate for cropping does not remain, the expense of reclamation is more or less thrown away. Three or 4 feet of organic material are desirable, especially if calcareous clay or marl underlies the deposit.

The quality of the peat is of special importance, not only as to the degree of decay, but also as to the nature of the original plant materials. The presence of the rubbery sedimentary type in the furrow-slice is especially deplorable. (See page 369.) Woody peat, on the other hand, is gen-

[15] See Ellis, N. K., and Richard Morris, "Preliminary Observations on the Relation of Yield of Crops Grown on Organic Soils with Controlled Water Table and the Area of Aeration in the Soil and Subsidence of the Soil," *Proc. Soil Sci. Soc. Amer.*, 10: 282–283, 1945. These authors report a shrinkage in general of 1 inch in 10 years. Other studies of the settling of peat are cited in this publication.

erally considered as more desirable than that coming from cattails, reeds and other plants and it usually is highly prized wherever it occurs. Much of the United States acreage of this type of peat soil lies in Wisconsin, Michigan, and New York.

13:12. PREPARATION OF PEAT FOR CROPPING

Since peat soils are often forested or covered with shrubs and other plants, the first step is to clear the land. Drainage may then be facilitated further, and the water table lowered and brought under control. The utilization of the area as pasture for a few years is sometimes practiced. The roots and stumps are thus given time to decay, their removal being relatively easy when the land is finally fitted for cultivation.

If the peat area is burned over to remove the brush and other debris, it should be done early in the season while the land is wet and not likely to catch fire. Such a fire is often difficult to extinguish and may ruin the deposit by destroying the more fertile surface layer. Moreover, the acrid smoke may seriously impair the quality of certain neighboring crops. Tokay grapes in central California are a case in point. If, however, the surface soil is fibrous with a more desirable layer below, it may be of advantage to burn this part, the resultant ash serving to mineralize the newly exposed layers.

After breaking the peat soil, preferably with heavy plows drawn by a tractor powerful enough to mash down second growth brush or sapling trees, it is advisable to grow such crops as corn, oats, or rye for a year or two, as they do well on raw and uneven peat lands. Once the peat is adequately weathered, freed of roots and stumps, and all hummocks eliminated, it is ready for vegetable production. More thorough drainage is now required and is usually obtained by a system of ditches. Sometimes tile drains or even mole drains are used.

13:13. MANAGEMENT OF PEAT SOILS [16]

All sorts of vegetable crops may be grown on peat soils—celery, lettuce, spinach, onions, potatoes, beets, carrots, asparagus, and cabbage perhaps

[16] A few of the many important publications dealing with the management of peat soil are:

Knott, J. E., *Fertilizing Onions on Muck Soils,* Bulletin 650, Cornell Univ. Agr. Exp. Sta., 1930.

Knott, J. E., *Celery Production on the Muck Soils of New York,* Bulletin 517. Cornell Univ. Agr. Exp. Sta., 1931.

being the most important as well as such specialized crops as peppermint. In some cases, peat is used for field crops, a more or less definite rotation being followed. Sugar beets, corn, oats, rye, buckwheat, flax, clover, timothy, and other field crops give good yields when suitable fertilization is provided. Moreover, certain nursery stocks do well on peat. In many cases, specially in Europe, peat soils are used extensively for pasture and meadows. In fact, almost any crop will grow on peat soil if properly managed. For a view of peat under cropping see Figure 13:3.

FIG. 13:3. *Harvesting onions on a peat soil. Note the dark color of the soil, the level topography and the uncleared wooded area in the rear. The production of high valued vegetable crops makes the use of mechanized equipment desirable. (N. Y. State College of Agriculture photo.)*

Structural management. Plowing is ordinarily unnecessary every year, as the peat is porous and open, unless it contains considerable silt and clay. In fact, a cultivated peat soil generally needs packing rather than

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Ogg, W. G., and A. MacLeod, "Reclamation and Cultivation of Peat Lands in Lewis," *Scottish Jour. Agr.*, 15: No. 2, 1932.
Fifield, W. M., *Potato Growing in Florida*, Bulletin 295, Fla. Agr. Exp. Sta., 1936.
Breckenbach, S. R., *A Fertility Program for Celery Production on Everglades Organic Soils*, Bulletin 333, Fla. Agr. Exp. Sta., 1939.
Harmer, Paul M., *The Muck Soils of Michigan, Their Management and Uses*, Special Bulletin 314, Mich. Agr. Exp. Sta., 1941.

loosening. The longer a peat has been cropped the more important compaction is likely to be, since the cultivation tends to destroy the original granular structure, leaving the soil, when dry, in a powdery condition. It is then susceptible to wind erosion, a very serious problem in some sections.

For this reason, a roller or packer is an important implement in the management of such land. The compacting of the peat allows the roots to come into closer contact with the soil and facilitates the rise of water from below. It also tends to reduce the blowing[17] of the soil during dry weather, although a windbreak of some kind is much more effective. The cultivation of peat, while easier than for mineral soils, is carried on in much the same way and should be shallow, especially after the root development of the crop has begun.

Use of farm manure and lime. In general, peat soils respond to applications of well-rotted farm manure. The manure furnishes plant nutrients, especially nitrogen, and probably increases the rate of decay of the peat itself. This speeding up of the carbon and nitrogen turnover cannot fail to increase the availability of the soil nutrients as well as the effectiveness of the commercial fertilizers used. As a consequence, farm manure, if available, is sometimes applied every few years even to well-decayed peat. Lime, that so often must be used on mineral soils in order to make farm manure fully effective, ordinarily is less necessary on peat, since this soil, as already noted, usually is adequately supplied with calcium.

Commercial fertilizers. Of much greater importance than farm manure are commercial fertilizers. In fact, complete reliance is placed on these materials in the production of most crops, especially vegetables. As organic soils are very low in phosphorus and potassium, these elements must by all means be added. Since vegetables usually are rapid-growing plants, succulence often being an essential quality, large amounts of readily available nitrogen are necessary. The nitrogen of newly broken peat is often available rapidly enough to supply this need, especially for oats, rye, corn, wheat, and similar crops. Such peat land, therefore, frequently requires at the beginning only phosphoric acid and potash. This is especially true of woody peats and is taken advantage of in the fertilization of such soils. After peat soils have been cropped for a few years, decay and nitrification are frequently too slow to meet the crop demand for nitrogen. Under such conditions this element is needed and a fertilizer containing nitrogen as well as phosphoric acid and potash is usually recommended.[18] The amount

[17] For a brief discussion of the control of wind erosion on peat soils, see page 272.

[18] Such analyses as a 0–8–12, a 0–12–12, a 0–12–18, or others of similar ratios are

of any given fertilizer applied will depend upon the kind of crop to be grown, the chemical and physical nature of the peat, its drainage, its previous fertilization and the length of time it has been under cultivation.[19]

Trace elements. Peat soils not only are in need of potassium, phosphorus, and nitrogen, but often some of the trace elements as well. Just what function the trace elements perform is not definitely known, but their fertilizer value is now well established on such soils, and they must be considered in any well-balanced fertilizer program.[20] On New York woody peats, copper sulfate has given good results in the control of certain diseases of lettuce and has aided in the coloration of onions. In fact, the application of this salt at the rate of 100 to 200 pounds to the acre is becoming a recognized treatment for these soils when they are first put under cultivation.

In Florida and elsewhere not only copper sulfate, but salts of manganese and zinc, are used to better the physiological condition of both peat and muck soils. Boron deficiencies are also becoming evident. Michigan peats, in general, need both boron and copper, compounds of these trace elements being mixed with the ordinary fertilizer at the rate of 50 to 100 pounds of borax and 100 to 200 pounds of copper sulfate per ton of fertilizer. Common salt in addition seems to give good results on Michigan peats, especially for beets, celery and cabbage. Perhaps both the sodium and the chlorine play important roles in crop nutrition on these soils.

13:14. PEAT VS. MINERAL SOILS

In assigning peat soils to a separate chapter, one is encouraged to think of them as distinctly and even radically different from most mineral soils. In many respects this certainly is true. Yet, fundamentally, the same types of change occur in the two groups; nutrients become available in much the same way and their management is based upon the same principles of fertility. In recognition of this, peat appears in the world classification of soils (Table 12:1, page 332) as *bog* soils, subject, of course, to such subdivisions as best show their differences in agricultural value.

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recommended when commercial nitrogen is unnecessary. When nitrogen is required, a 3–12–18, a 4–8–24, a 5–10–5, a 15–30–15, a 5–10–15, or other mixtures of similar ratio may be utilized depending on soil conditions and the crop to be grown. In many cases nitrate of soda or other fertilizers are applied as a side-dressing.

[19] Articles dealing with the fertilization of crops growing on peat soils are cited on page 386.

[20] The use of trace elements as fertilizers is discussed more fully on page 509.

CHAPTER

14

The Soil Reaction; Soil Acidity and Alkalinity

ONE OF the outstanding physiological characteristics of the soil solution is its reaction.[1] Since microorganisms and higher plants respond so markedly to their chemical environment, the importance of soil reaction, and of the factors associated with it, has long been recognized. Three conditions are, of course, possible: *acidity, neutrality,* and *alkalinity.*

Soil acidity is common in all regions where precipitation is high enough to leach appreciable amounts of exchangeable bases from the surface layers of soils. So widespread is its occurrence and so marked is its influence on plants that it has become one of the most discussed properties of soils. Because of the large area of arable acid soils the importance of soil acidity in a practical way greatly surpases that of soil alkalinity.

Alkalinity occurs when there is a comparatively high degree of base saturation. The presence of salts, especially calcium, magnesium, and sodium carbonates, also gives a preponderance of OH-ions over H-ions in the soil solution.[2] Under such conditions the soil is alkaline and sometimes,

[1] The literature dealing with soil reaction, especially that respecting soil acidity, is varied and no specific citations of a general nature can be given. Recent files of such periodicals as the *Journal of the American Society of Agronomy* (Since Jan., 1949, *Agronomy Journal*), *Journal of Agricultural Research, Journal of Agricultural Science, The Proceedings of the Soil Science Society of America,* and *Soil Science* contain many of the important articles published in English.

[2] When salts of strong bases and weak acids, such as NA_2CO_3, K_2CO_3, and $MgCo_3$ go into solution they undergo hydrolysis and develop alkalinity. For Na_2CO_3 the reaction is as follows:

$$2\,Na^+ + CO_3^= + 2\,HOH \rightleftharpoons 2\,Na^+ + 2\,OH^- + H_2CO_3$$

Since the dissociation of the NaOH is greater than that of the weak H_2CO_3, a domination of OH ions results.

especially if sodium carbonate is present, very strongly so, a pH of 9 or 10 being not uncommon. Alkaline soils are, of course, characteristic of most arid and semiarid regions. Their discussion will follow that of acid soils.

14:1. THE COLLOIDAL CONTROL OF SOIL REACTION

A feature of fundamental importance must be examined before considering the practical problems of soil acidity. The trait referred to is the control mechanism of soil pH. As is well known, this control lies largely in the soil colloidal complex. Why is this and how does it operate?

Hydrogen vs. metallic cations. It has already been explained (page 96) that the colloidal complex of the soil may be considered as a mixture of rather insoluble acids and salts of these acids. The adsorbed hydrogen and metallic cations which surround the insoluble micelles tend to be in dynamic equilibrium with the soil solution. Consequently, the pH of the soil solution is markedly affected by these adsorbed cations as dissociation takes place. For convenience the situation may be pictured using separate examples for colloidal acids and salts of these acids. Because of the prominence of calcium this cation is used to represent all adsorbed bases.

$$\mathrm{H}\boxed{\quad\text{Micelle}\quad} \rightleftharpoons \boxed{\quad\text{Micelle}\quad}^{-} + \mathrm{H}^{+} \quad \text{[acidity]}$$

$$\mathrm{Ca}\boxed{\quad\text{Micelle}\quad} + 2\,\mathrm{HOH} \rightleftharpoons \begin{matrix}\mathrm{H}\\ \mathrm{H}\end{matrix}\boxed{\quad\text{Micelle}\quad} + \mathrm{Ca}^{++} + 2\,\mathrm{OH}^{-} \quad \text{[alkalinity]}$$

Thus, in spite of its insolubility a micelle containing adsorbed hydrogen furnishes H-ions to the soil solution. Unless this effect is countered by that of adsorbed bases, the H-ion will dominate in the soil solution and a pH below 7 results. The mechanism is the same as that of any acid, say HCl, but, of course, much less pronounced since we are dealing with very weak acids.

In contrast, when metallic cations (bases) are adsorbed by these weak acid radicals, hydrolysis will develop a definite alkaline reaction. That is, a domination of the OH-ions over the H-ions occurs as shown above.

It should be kept in mind that under natural conditions the above reactions occur simultaneously. That is, H-ions and metallic cations are held at one time by the same micelle (see Fig. 4:2.) The pH of the soil solution, therefore, will depend upon the relative amounts of adsorbed hydrogen and

adsorbed metallic cations. Where the effect of the hydrogen is dominant, acidity results. Excess bases yield alkalinity, while at just the right balance the pH of the soil solution will be 7. (See Fig. 2:4.)

Percentage base saturation. The relative proportions of the adsorbed hydrogen and the exchangeable bases of a colloidal complex are dependent upon the *percentage base saturation.* (See page 113.) Obviously a low percentage base saturation means acidity while a percentage base saturation approaching 100 will result in neutrality or alkalinity. In general, humid-region soils dominated by *silicate clays* and *humus* are acid if their percentage base saturation is much below 90. When such soils have a percentage base saturation of 90 or above they usually are neutral or alkaline. The exact pH value in any case, however, is determined by at least two other factors in addition to the percentage base saturation.

Nature of the micelle. The situation respecting latosols (page 347) is practically the same as for soils whose clays are of the silicate type except that the percentage base saturation must fall much lower before acidity results. The explanation lies in the nature of the micelle radicals which are in large degree made up of hydrous oxides of iron and aluminum. (See page 107.) The dissociation of such clays when dominated by H-ions is much less than that of silicate clays at a correspondingly low percentage base saturation. Thus, a silicate clay with a base saturation of 50 per cent might show a pH within a range of 5.2 to 5.8, while that of the hydrous oxide clays similarly devoid of bases might lie between 6.0 and 7.0.

With peat soils the situation is just the opposite. The adsorbed hydrogen of the organic complex dissociates with comparative ease. Consequently, the pH of organic soils generally is lower than that of humid region mineral soils when both are at the same percentage base saturation. In short, the organic soils carry the stronger acids. Following the illustration given above, a percentage base saturation of 50 might give for the peat soil a pH lying between 4.5 and 5.0 in contrast with a range of 5.2 to 5.8 already cited for a silicate soil at the same percentage base saturation.

It should be noted that the different acid silicate clays—the kaolinite, montmorillonite, and hydrous mica types—apparently dissociate in somewhat different degrees, the kaolinite least and the montmorillonite greatest. (See page 400.) Likewise, the organic colloids exhibit considerable variety among themselves. In spite of this, however, the latter group apparently has a lower pH value than any of the clays when at corresponding percentage base saturations.

Kind of adsorbed bases. Another factor which influences the pH of a soil has to do with the comparative amounts of the *particular bases* present in the colloidal complex. For instance, at a percentage base saturation say of 70, the presence of Ca-, Mg-, K-, and Na-ions in the ratio of 10-3-1-1 would certainly result in a lower pH than though the ratio was 4-1-1-9. In the one case calcium is dominant, in the other we are dealing with a sodium-calcium complex dominated by sodium.[3]

With the reaction of the soil solution influenced by three distinct and uncoordinated factors—percentage base saturation, nature of the micelle, and the ratio of the exchangeable bases—one would hardly expect to find a close correlation between percentage base saturation and pH when comparing soils at random. Yet with soils of similar origin, texture, and organic content a rough correlation does exist. Nevertheless, it should not be relied on with any great degree of certainty. Two soils with the same pH seldom possess exactly the same percentage base saturation and vice versa.

14:2. MAJOR CHANGES IN SOIL pH

CO_2 and soil acidity. The most important and most persistent cause of changes in the reaction of soil solutions is the effect of carbon dioxide. This gas in the presence of water tends to form carbonic acid. The greater the pressure of CO_2, the higher will be the H-ion concentration resulting. The role of carbonic acid in respect to base exchange has already been duly stressed (page 98). Yet the generalized reaction will be cited again in order to lend emphasis and clarity to this vital phenomenon. For the sake of simplicity it is assumed that the numbers of Ca, H, and other metallic cations (B) are in the ratio of 40, 40, and 20 per micelle respectively.

$$\begin{matrix}Ca_{40}\\ H_{40}\\ B_{20}\end{matrix}\boxed{\quad\text{Micelle}\quad} + 5\,H_2CO_3 \rightleftharpoons \begin{matrix}Ca_{38}\\ H_{45}\\ B_{19}\end{matrix}\boxed{\quad\text{Micelle}\quad} + \begin{matrix}2\,Ca(HCO_3)_2\\ B(HCO_3)\\ \text{subject to loss}\\ \text{by leaching}\end{matrix}$$

In regions receiving sufficient rainfall to cause leaching, the soluble bicarbonates are removed and the reaction, as indicated above, proceeds

[3] A soil whose clay complex is predominantly montmorillonite and illite will generally show a pH value at least one unit higher when dominated by Na-ions than when it is dominated by Ca-ions. For instance, when the pH in the latter case is 5.5, the pH of the former can be expected to fall within the range of 6.5 to 7.0. See Pratt, P. F., and O. W. Thorne, "Solubility and Physiological Availability of Phosphate in Sodium and Calcium Systems," *Proc. Soil Sci. Soc. Amer.*, 13: 213–217, 1948.

to the right. Thus, the colloidal complexes of humid-region soils are steadily losing their adsorbed metallic cations and as a result, the H-ion concentration of their solutions is increasing. In other words, a persistent and unremitting inclination towards acidity and its intensification exists in humid-region soils.

Removal of bases. Any artificial treatment or manipulation of the soil that increases the loss of calcium and magnesium will, in the course of time, encourage a major change in soil pH. Merely leaving the soil bare allows these cations to be lost more rapidly. In fact, most of the ordinary physical methods of soil management intensify rather than counteract soil acidity. The cultivation of the soil is a case in point.

The decomposition of organic matter may intensify the loss of bases through the formation of acids, both organic and inorganic. These acids are often much stronger than carbonic and can thus effect base removal even at low pH values. Examples of inorganic acids commonly formed are nitric and sulfuric, the products of nitrification and sulfur oxidation, respectively.

Influence of fertilizers. Certain fertilizers should also be mentioned in this respect. Sulfate of ammonia, for example, upon nitrification yields both nitric and sulfuric acids. These encourage the loss of lime in drainage, and hastens the development of acidity. (See page 513.) Flowers of sulfur rapidly develop sulfuric acid by oxidation. Nitrate of soda, calcium nitrate, calcium cyanamid, and basic slag, on the other hand, tend to check the swing towards a more acid condition.

Soils of arid regions. In contrast with the fluctuations of soil pH due to the development of acidity in humid region soils is the neutrality or even alkalinity of soils in arid and semi-arid regions. In these areas there is insufficient rainfall to leach out the adsorbed bases. Consequently, high percentage base saturations are common. In fact, if drainage is impeded excess salts may accumulate. If Na_2CO_3 is involved the pH values go up above 8.0.

14:3. MINOR FLUCTUATIONS IN SOIL pH

Not only do soil solutions suffer major and often drastic changes in H-ion concentration (as indicated above) but they exhibit minor fluctuations as well.[4] For instance, the drying of soils, especially above field temperatures, will often cause a noticeable increase in acidity. This is

[4] Swanback, T. R., and M. F. Morgan, *Seasonal Fluctuations in Soil Reaction.* Conn. Agr. Exp. Sta., Bul. 311: 264–268, 1930.

probably due to a change in the organization of the colloidal matter and should be kept in mind in preparing soil samples for pH determination.

The pH of mineral soils tend to decline during the summer, especially if under cultivation, due to carbonic and other acids produced by microorganisms. The activities of the roots of higher plants, especially with regard to acidic exudates, may also be a factor. In winter and spring an increase in pH often is noted, possibly because biotic activities during this time are considerably slower. As a result, the alkalizing influence of the solution of minerals will tend to raise soil pH.

14:4. H-ION HETEROGENEITY OF THE SOIL SOLUTION [5]

In considering the H-ion concentration of the soil solution it is not to be inferred that one is dealing with an ordinary homogeneous solution. In fact, because of adsorption, the exact opposite is true. (See Fig. 14:1.) For example, the H-ions are concentrated near the colloidal interfaces and become less numerous as the distance from the micelle is increased. The attractive forces of the colloidal surfaces are such as to make the differences in H-ion concentration between the inner and outer layers of the capillary water in most cases very great indeed. As a result, the drainage water even from a markedly acid soil may be near neutrality due in part to this heterogeneity of the soil solution.

That the variability of the soil solution is important in many respects cannot be denied. For example, it affords microorganisms and plant roots a great variety of solution environments. Organisms that are unfavorably influenced by a given H-ion concentration may find, at an infinitesimal distance away, another that is more satisfactory. This may account in part for the many different floral species present in normal soils.

14:5. ACTIVE VERSUS EXCHANGEABLE ACIDITY

In an acid soil two groups of hydrogen ions are involved—those of the soil solution itself and those held as adsorbed cations by the colloidal

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Smith, A. M., and I. M. Robertson, "The Influence of the Plant upon the Seasonal Changes in Soil Acidity," *Jour. Agr. Sci.*, 21: 822–831, 1931.

Hester, J. B., and F. A. Shelton, "Seasonal Variation in pH of Field Soils a Factor in Making Lime Recommendations," *Jour. Amer. Soc. Agron.*, 25: 299–300, 1933.

Stephenson, R. E., "The Nitrification Process and Plant Nutrition," *Soil Sci.*, 41: 188, 1936.

Huberty, M. R., and A. R. C. Haas, "The pH of Soil as Affected by Soil Moisture and Other Factors," *Soil Sci.*, 49: 455–478, 1940.

[5] Purvis, E. R., and O. W. Davidson, "Review of the Relation of Calcium to Availability and Adsorption of Certain Trace Elements by Plants," *Soil Sci.*, 65: 114, 1948.

complex. These groups are in dynamic equilibrium and consequently both must be considered in any attempt to alter the H^+ to OH^- ratio of the soil solution.

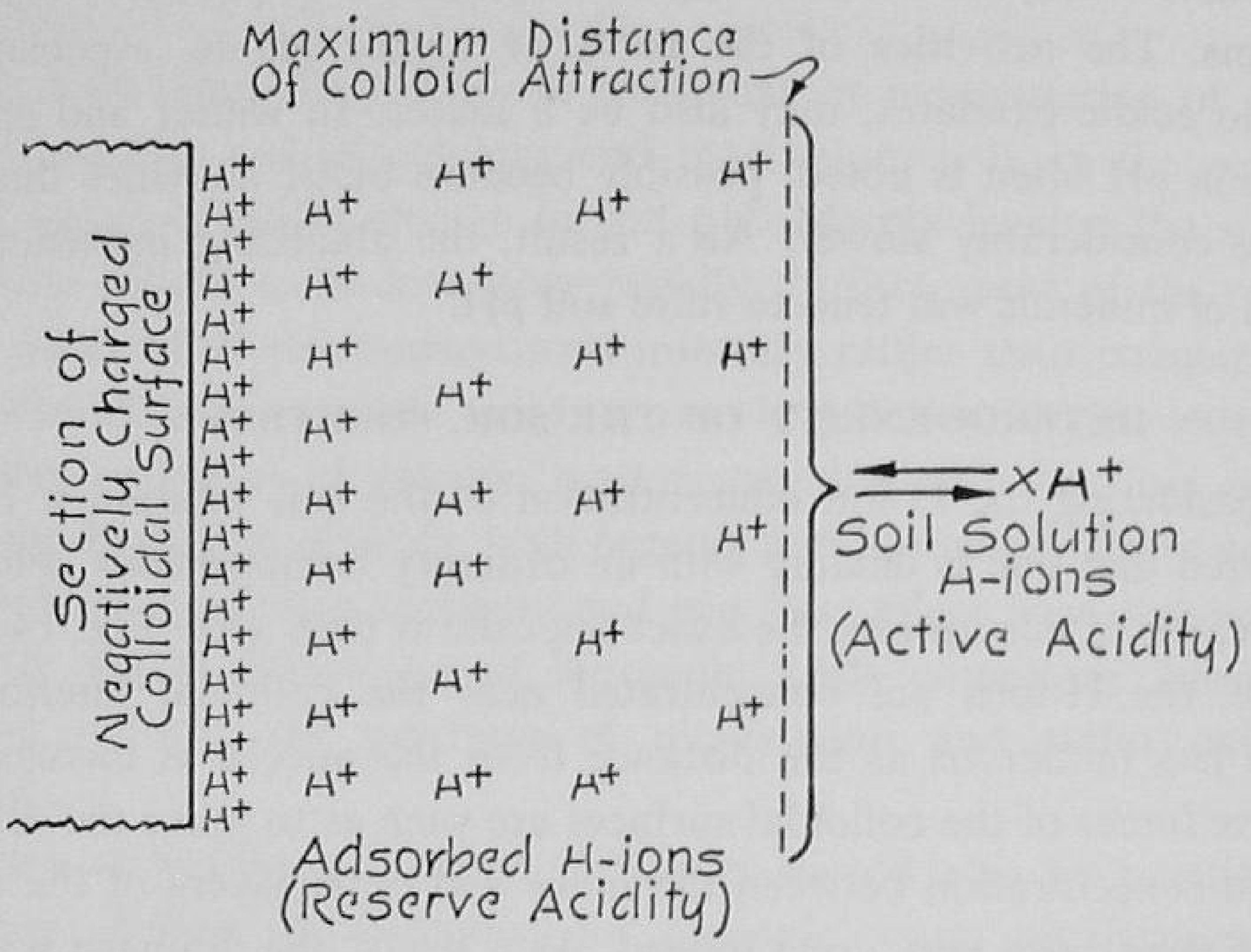

FIG. 14:1. *Diagram showing the equilibrium relationship between* reserve *and* active *acidity. Note the large number of adsorbed H-ions compared to those in the soil solution. Obviously, neutralizing only the H-ions in the soil solution will be of little consequence since they will quickly be replenished by some of the numberless H-ions adsorbed at the colloidal surfaces. This means high buffering.*

For convenience of distinction the H-ion concentration of the soil solution is designated as *active acidity*. Those exchangeable H-ions held on the soil colloids are referred to as the *reserve* or *potential acidity*[6] of the soil. This situation is shown graphically by Figure 14:1 and by the following equation:

$$\begin{matrix}\text{Adsorbed H-ions} \\ \text{(Potential acidity)}\end{matrix} \rightleftharpoons \begin{matrix}\text{Soil solution } H^+ \\ \text{(Active acidity)}\end{matrix}$$

[6] The presence of exchangeable or reserve acidity is easily demonstrated. If a sample of acid soil is shaken thoroughly with distilled water and filtered, the percolate will usually show a comparatively slight acidity. On the other hand, if a concentrated solution of a neutral salt, such as KCl, is used instead of distilled water, the filtrate will be comparatively acid. The lowering of the pH is due to the liberation of the reserve acidity by ionic exchange. The K-ions, because of their concentration, are able to replace part of the exchangeable H-ions of the colloidal complex. The strongly acid solution which results demonstrates clearly the existence of reserve acidity.

Since the adsorbed hydrogen tends to move outward and become active when the acidity of the soil solution is reduced, the term potential is particularly significant. Distinct as the two groups apparently are, they grade into each other as progress outward from the colloidal interface is made.

Amounts of active and reserve acidity. The relative magnitude of the two types of acidity—active *vs.* exchangeable—is not only interesting but is of vital practical importance as well. In referring to the acidity of a soil as high or very high, the impression may be given that the active acidity under certain conditions may be exceedingly great, even dangerously so. Actually, however, the reverse is true. For example, only about *1/50* of a *pound* of calcium carbonate would be required to neutralize the active acidity in an acre-furrow-slice of an average mineral soil having a pH of 6.[7] If the same soil should possess a pH of 5, 1/5 pound of calcium carbonate would be adequate, while if the pH should be lowered to 4, two pounds would be ample. Thus, the *active* acidity is evidently ridiculously small even at its maximum.

Since limestone at the rate of 1, 2, or even 3 tons to the acre is often recommended, this neutralizing agent is obviously applied in amounts hundreds of times in excess of the active acidity. The reason for such heavy applications is largely due to the magnitude of the exchangeable hydrogen. These adsorbed hydrogen ions move into the soil solution when the H-ion concentration thereof becomes depleted. The potential acidity thus supplies hydrogen ions which must be neutralized before the pH of the soil solution can be changed appreciably.

Conservative calculations indicate that the reserve acidity may be perhaps 1,000 times greater than the active acidity in the case of a sandy soil, and 50,000 or even 100,000 times greater for a clayey soil high in organic matter. The figure for a peat soil is likely to be even greater. The practical significance of this tremendous difference in magnitude of the active and reserve acidities of soils should be apparent after reading the next section.

14:6. THE BUFFERING OF SOILS

As pointed out above, there is a distinct resistance to a change in soil pH other than that offered by the soil solution itself. This resistance, called

[7] This assumes that the $CaCO_3$ could be brought in contact with the soil solution and that only the hydrogen ions actually in this solution would react with the $CaCO_3$. A soil moisture content of 20 per cent was assumed in making this calculation.

buffering, is generally characteristic of mixtures of weak acids and their salts.[8] While such weak acid radicals as the carbonate, bicarbonate, and the phosphates are present in soils, the important ones from the standpoint of this phenomenon are those of the colloidal complex. In short, the average soil is colloidally buffered by the clay and humus present.

The mechanics of soil buffering can be explained rather simply if we first consider the dissociation of H-ions from the weak colloidal acids. This can be represented as before (see page 391) for a single hydrogen ion as follows:

$$\underset{\text{(Potential acidity)}}{\text{Adsorbed H-ions}} \rightleftharpoons \underset{\text{(Active acidity)}}{\text{Soil solution } H^+}$$

Note that this characteristically weak acid dissociates only sparingly and that most of the hydrogen remains in an undissociated, adsorbed form.

Now let us consider what would happen if we were to add just enough liming material to neutralize the H-ions in the soil solution. Immediately the above reaction would be shifted to the right, resulting in more hydrogen ions moving out into the soil solution. As a consequence, the pH rise which results would be negligibly small and would remain negligibly small until enough lime has been added to appreciably deplete the exchangeable (reserve) hydrogen.

This resistance to pH change is equally important in preventing a rapid lowering of the pH of soils. For example, consider the case where H-ions are added to a soil or where they result from certain biochemical changes. This would give a temporary increase in the H ions in the soil solution.

[8] A classic example of a simple buffer solution is a mixture of acetic acid and sodium acetate. The dissociation of a solution of acetic acid is notably small. This may be indicated as follows:

$$CH_3COOH \rightleftharpoons CH_3COO^- + H^+$$

Since sodium acetate is almost completely dissociated into the CH_3COO^- and Na^+ ions, adding this salt to a solution of acetic acid would drive the above reaction even further to the left, thereby markedly repressing the dissociation of the acid. Thus, in the buffer mixture a very large proportion of the hydrogen is held in a molecular combination as undissociated CH_3COOH.

When an acid such as HCl is added to the buffer mixture most of the H ions react with the acetate ions to form undissociated CH_3COOH. In other words, the reaction above goes to the left and little change in pH results.

On the other hand, additions of a base such as NaOH would tend to temporarily neutralize the H ions and allow the reaction to go to the right. However, in establishing equilibrium, the CH_3COOH molecules would dissociate to yield more H ions and the resistance to pH change would again be apparent.

In this case the equilibrium reaction above would immediately shift to the left and more H ions would become adsorbed on the micelle. Again, the resultant pH change, this time a lowering, in the soil solution would be very small.

These two examples point out rather clearly the principles involved in buffering. In addition, they show that the basis of buffer capacity lies in the *reserve* hydrogen of the complex. These H-ions, together with the adsorbed metallic cations, not only indirectly control the pH of the soil solution, but also determine the quantity of lime or acidic constituents necessary to bring about a given pH change.

14:7. BUFFER CAPACITY OF SOILS AND RELATED PHASES

Before discussing the practical importance of soil buffering, it might be well to consider certain technical phases of the phenomenon that are of utmost significance. The first suggestion thereto is as obvious as it is simple. The higher the exchange capacity of a soil the greater, other factors being equal, will be its buffer capacity. This is because more H-ions and metallic cations must be interchanged to effect a given rise or lowering of the percentage base saturation. In practice this is fully recognized in that the heavier the texture of a soil and the higher its organic content, the larger must be the application of lime to force a given change in pH.

Buffer curves. Another phase of buffering, less understood but equally important logically presents itself at this point. Is the buffer capacity of soils the same throughout the percentage base saturation range? This is the best answered by reference to an average theoretical titration curve presented by Peech [9] for a large number of Florida soils. (See Fig. 14:2.)

Three things are clearly obvious from the curve. First, there is a rather definite correlation, in general, between the percentage base saturation of these soils and their pH. This has already been suggested (page 113) and therefore is not wholly unexpected.

Second, the generalized curve indicates that the degree of buffering varies, being lowest at the extreme base saturation values. Between these extremes where the curve is flatter, the buffering reaches a maximum. Theoretically, the greatest buffering occurs at about 50 per cent base saturation. This situation is extremely important both technically and practically.

[9] Peech, Michael, "Availability of Ions in Light Sandy Soils as Affected by Soil Reaction," *Soil Sci.*, 51: 473–486, 1941. This author finds that the same type of composite curve also holds for New York mineral soils.

Third, the buffering, as indicated by the curve, is more or less uniform over a pH range of say 4.5 to 6.5. This is vitally significant as it indicates, for example, that under field conditions about the same amount of lime will be required to change the soil pH from 5.0 to 5.5 as from 5.5 to 6.0.

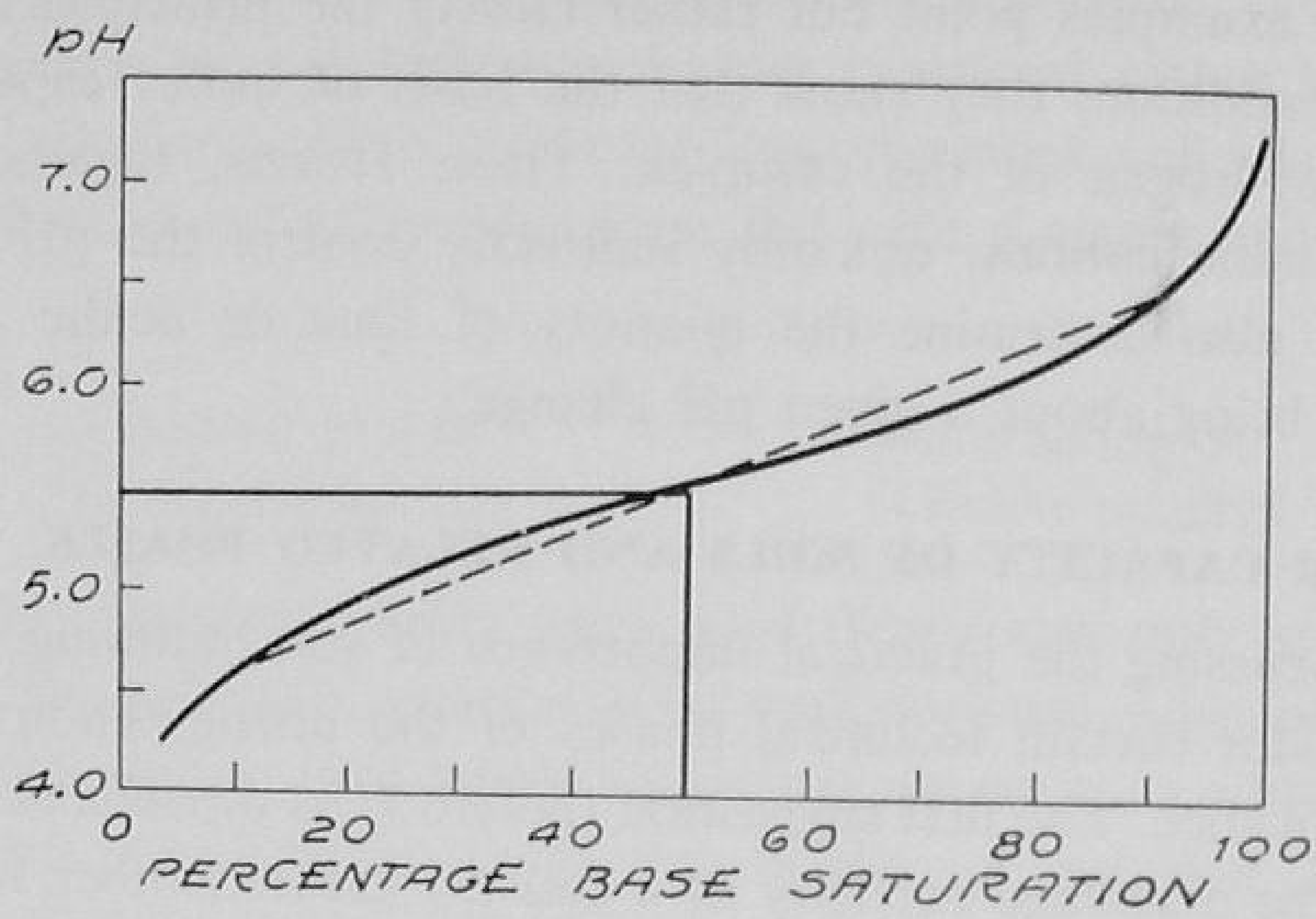

FIG. 14:2. *Theoretical titration curve for a large number of Florida soils. (After Peech.) The dotted line indicates the zone of greatest buffering. The maximum buffering should occur at approximately 50 per cent base saturation.*

Before leaving this phase it is well to remark that the curve of Figure 14:2 is a composite and represents the situation in respect to any particular soil only in a general way. That the titration curves for individual soils will deviate more or less widely is to be expected since the colloidal complex of different soils varies with the kinds and amounts of clay and humus present.

Variation in titration curves. As an instance of the difference between the clay groups, Mehlich's [10] results are especially significant. He found the pH values of montmorillonite and the hydrous micas to lie between 4.5 and 5.0 when these clays were at 50 per cent base saturation. The pH values of kaolinite and halloysite under comparable conditions were found in general to lie within a range of 6.0 to 6.5.

The influence of the different clays upon the titration curves of individual soils is nicely shown by the data in Figure 14:3. Samples from the B horizon were used to avoid the complicating effects of organic matter. In light of the figures quoted from Mehlich in the preceding paragraph, it is easy to see

[10] Mehlich, Adolf, "Base Unsaturation and pH in Relation to Soil Type," *Proc. Soil Sci. Soc. Amer.*, 6: 150–156, 1941.

from these curves that the Cecil subsoil with a pH of about 6.4 at 50 per cent base saturation must be highly kaolinitic. The corresponding pH for the Iredell is about 4.4, indicating that clays of the montmorillonite or similar types are dominant in this soil. Obviously, the clays of the Iredell develop stronger acids than those of the Cecil and, under comparable conditions, exhibit a higher buffer capacity.

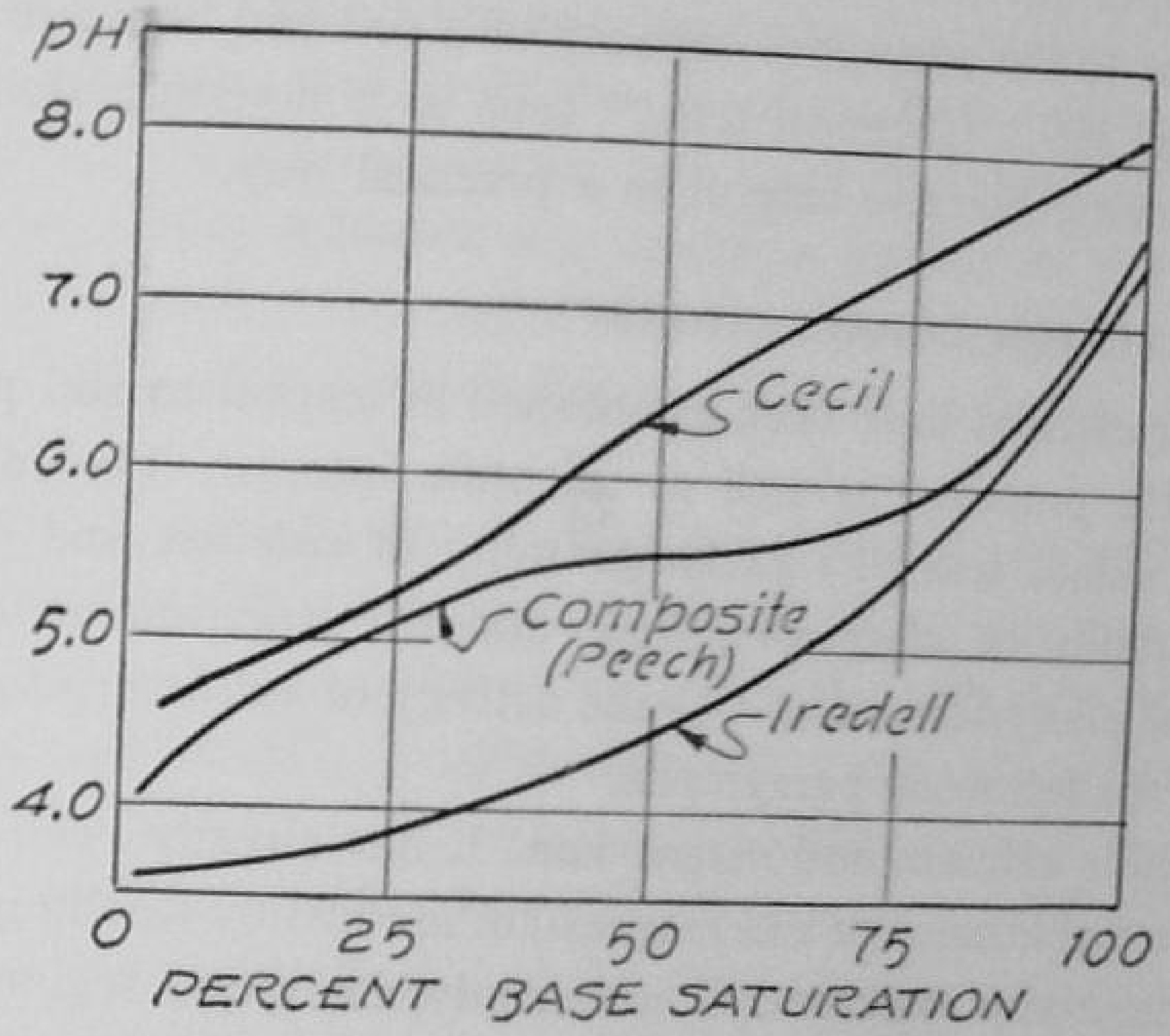

FIG. 14:3. Titration curves for the B horizon of two North Carolina soil profiles. The Cecil is dominated by kaolinitic minerals (1 to 1 types) and the Iredell by montmorillonitic clays (2 to 1 types). Note the difference in the trends of the two curves and how they in turn differ from the composite ideal as set up by Peech (Figure 14:2). This is to be expected.

At 50 per cent base saturation, the Cecil shows a pH near 6.4. The corresponding figure for the Iredell is about 4.4. Obviously the Iredell presents a stronger acid and hence is more highly buffered. Since the samples from the two came from the subsoils, the trend of their curves is not influenced to any degree by humus.

(The Cecil and Iredell curves are from Adolf Mehlich's paper cited on page 400.)

14:8. IMPORTANCE OF BUFFERING

Stabilization of soil pH. A marked change in pH undoubtedly indicates a radical modification in soil environment, especially in respect to the availability of plant nutrients. And if this environment should fluctuate too widely higher plants and microorganisms undoubtedly would suffer seriously before they could make adequate adjustments. Not only would they be affected directly by the change in H-ion concentration but also the indirect influences on nutrient elements might prove to be exceedingly

unsatisfactory. (See Figs. 14:4 and 14:5.) The stabilization of soil pH through buffering seems to be an effective guard against these difficulties.

Quantities of amendments required. Obviously the greater the buffering capacity of a soil, the larger must be the amounts of lime or sulfur used to effect a given change in pH. Hence, in deciding as to the amount of lime to apply to a soil of known pH, texture and organic content are among the important soil factors to be considered. These properties give a rough idea as to the adsorptive capacity of a soil and hence of its buffering. (See page 399.) Chemical tests,[11] such as a determination of cation exchange capacity, are also helpful in a practical way.

14:9. SOIL-REACTION CORRELATIONS[12]

Certain correlations have been established in respect to soil pH that are of considerable practical as well as scientific interest. The interrelations between pH values and (1) exchangeability of *calcium* and *magnesium,* (2) the solubility of *aluminum, iron,* and the *trace elements,* (3) the availability of *phosphorus,* and (4) the activity of *soil microorganisms* are discussed in the following paragraphs.

Exchangeable calcium and magnesium. It has already been shown that as the exchangeable calcium and magnesium are lost by leaching, the acidity of the soil gradually increases. Consequently, in humid region soils there is a fairly definite correlation between the pH and the amounts of these two constituents present in exchangeable form. (See Fig. 14:4.) In arid regions, the same general relationships hold except under conditions where an appreciable amount of sodium is adsorbed. (See page 415.)

Aluminum, and the trace elements. The relationships between soil reaction and the activity of aluminum, iron, and manganese are shown in Figure 14:4. When the pH of a mineral soil is low, appreciable amounts of these three constituents are soluble, so much so in fact that they may become extremely toxic to certain plants.[13] However, as the pH is in-

[11] See Peech, M., and R. Bradfield, "Chemical Methods for Estimating Lime Needs of Soils," *Soil Sci.,* 65: 35–55, 1949.

[12] See Pettinger, N. A., *A Useful Chart for Teaching the Relation of Soil Reaction to the Availability of Plant Nutrients to Crops,* Bulletin 136, Va. Polytec. Inst., 1935; and Truog, Emil, "Lime in Relationship to Availability of Plant Nutrients," *Soil Sci.,* 65: 1–7, 1948.

[13] McLean, F. T., and B. E. Gilbert, "Aluminum Toxicity," *Plant Physiol.,* 3: 293–303, 1928.

Berger, K. C., and G. C. Gerloff, "Manganese Toxicity of Potatoes in Relation to Strong Soil Acidity," *Proc. Soil Sci. Soc. Amer.,* 12: 310–314, 1947.

Morris, H. D., and W. H. Pierre, "The Effect of Calcium, Phosphorus and Iron

creased, precipitation takes place and the amounts of these ions in solution become less and less until at neutrality or somewhat above certain plants may suffer from a lack of available manganese and iron. This is especially likely to be the case if a markedly acid sandy soil is suddenly brought to a neutral or alkaline condition by an over application of lime.

While deficiencies of manganese, and especially iron, are not widespread, they do occur in certain areas, particularly on overlimed sandy soils or alkaline arid region soils. If the soil reaction is held within a soil pH range say of 6.0 to 7.0, the toxicity of the aluminum, iron, and manganese may satisfactorily be suppressed. At the same time their unavailability will be avoided unless these elements are decidedly lacking in the soil. Copper and zinc are affected in the same way by a rise in pH, the critical point being near 7 pH, above which their availability definitely declines. (See Fig. 14:4.)

With boron,[14] the situation is somewhat different and probably is more complicated. Although neither the soil untreated nor the lime alone appreciably precipitate boron, some authors feel that the two, when in combination, fix it markedly. Possibly also the excess of calcium hinders in some way the movement of boron into the plant, in spite of its solubility. Too much calcium in the plant cells might even interfere with boron metabolism even though plenty of the latter should be present. It has also been suggested that lime may create a serious competition for boron by a stimulation of soil micro-organism activity.

Available phosphorus. The kind of phosphate ion present varies with the pH of the soil solution. When the soil is distinctly alkaline, the PO_4-ion

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on the Tolerance of Lespedeza to Manganese Toxicity in Culture Solution," *Proc. Soil Sci. Soc. Amer.*, 12: 382–386, 1947.

Fujimoto, C. K., and G. D. Sherman, "Behavior of Manganese in the Soil and the Manganese Cycle," *Soil Sci.*, 66: 131–145, 1948.

[14] A few of the more important articles dealing with the availability of soil boron are cited below:

Reeve, E., and J. W. Shive, "Potassium-Boron and Calcium-Boron Relationships in Plant Nutrition," *Soil Sci.*, 57: 1–14, 1944.

Jones, H. E., and G. D. Scarseth, "The Calcium-Boron Balance as Related to Boron Needs," *Soil Sci.*, 57: 15–24, 1944.

Berger, K. C., and Emil Truog, "Boron Availability in Relation to Soil Reaction and Organic Matter Content," *Proc. Soil Sci. Soc. Amer.*, 10: 113–116, 1945.

Brennan, E. G., and J. W. Shive, "Effect of Calcium and Boron Nutrition of the Tomato on the Relation Between These Elements in the Tissue," *Soil Sci.*, 66: 66–75, 1948.

Berger, K. C., "Boron in Soils and Crops," *Advances in Agronomy*, Vol. 1: 321–348, A. G. Norman, ed., Academic Press Inc., New York, 1949.

apparently is the commonest form. But as the pH is lowered and the soil becomes slightly to moderately acid, the HPO_4-ion and the H_2PO_4-ion prevail. At higher acidities H_2PO_4-ions tend to dominate. Because of the formation of insoluble compounds,[15] a soil reaction which yields a mixture of HPO_4 and H_2PO_4-ions is usually preferred.

The activity of the soil phosphorus is related to pH in another way, in this case indirectly. It has already been explained that as soil acidity increases there is an enhancement in the activity of the iron, aluminum and manganese. Under such conditions soluble phosphates are markedly fixed as very complex and insoluble compounds of these elements. This fixation is most serious when the soil pH is below 5.0. The situation is shown graphically in Figure 17:2.

On the other hand, if the pH of a mineral soil is raised much above 7, say 7.5 or 8.0, the phosphate nutrition of higher plants, and perhaps of microorganisms as well, is disturbed in another manner.

In the first place at a soil pH above 7, if abundant lime is present, complex calcium phosphates are formed. These range, in increasing insolubility, from the oxy-apatite [3 $Ca_3(PO_4)_2{\cdot}CaO$] to the most insoluble phosphate of all, the fluorapatite [3 $Ca_3(PO_4)_2{\cdot}CaF_2$] which may form if fluorine is present. Thus, by a rise in pH, say 7.5 to 8.5, the solubility, both of the native and the added phosphorus, may be very seriously impaired. (See Fig. 17:2 and page 478.)

The situation is further complicated by interrelations of a more speculative nature. If the pH is raised much above 7 by the addition of lime, the excess calcium may hinder in some way the passage of the phosphate ions through the cell walls of the root hairs. It may even interfere with the proper metabolism of such ions once they are absorbed.[16] A similar interference has been suggested in respect to boron. But whatever the explanation may be there undoubtedly is a fairly definite correlation between high soil pH and the utilization of phosphorus by most plants.

The correlation of phosphorus availability and soil reaction would be sadly incomplete without an examination of the situation in the intermediate pH range of mineral soils, say from 6 to 7. Between these two

[15] McGeorge, W. T., "The Relation of Potential Alkalinity to the Availability of Phosphate in Calcareous Soils," *Soil Sci.*, 39: 443–452, 1935.

[16] Pierre, W. H., and G. M. Browning, "The Temporary Injurious Effects of Excessive Liming of Acid Soils and Its Relation to the Phosphate Nutrition of Plants," *Jour. Amer. Soc. Agron.*, 27: 742–759, 1935.

pH limits phosphorus fixation seems to be at a *minimum* and conversely phosphorus availability as far as most plants are concerned, is at a maximum. (See Fig. 14:4.) In the regulation of the phosphorus nutrition of crops it is rather important, therefore, that soil pH be kept within the conservative limits of 6 to 7 or very near thereto. Even then higher plants often do not absorb one-half or even one-third of the available phosphoric

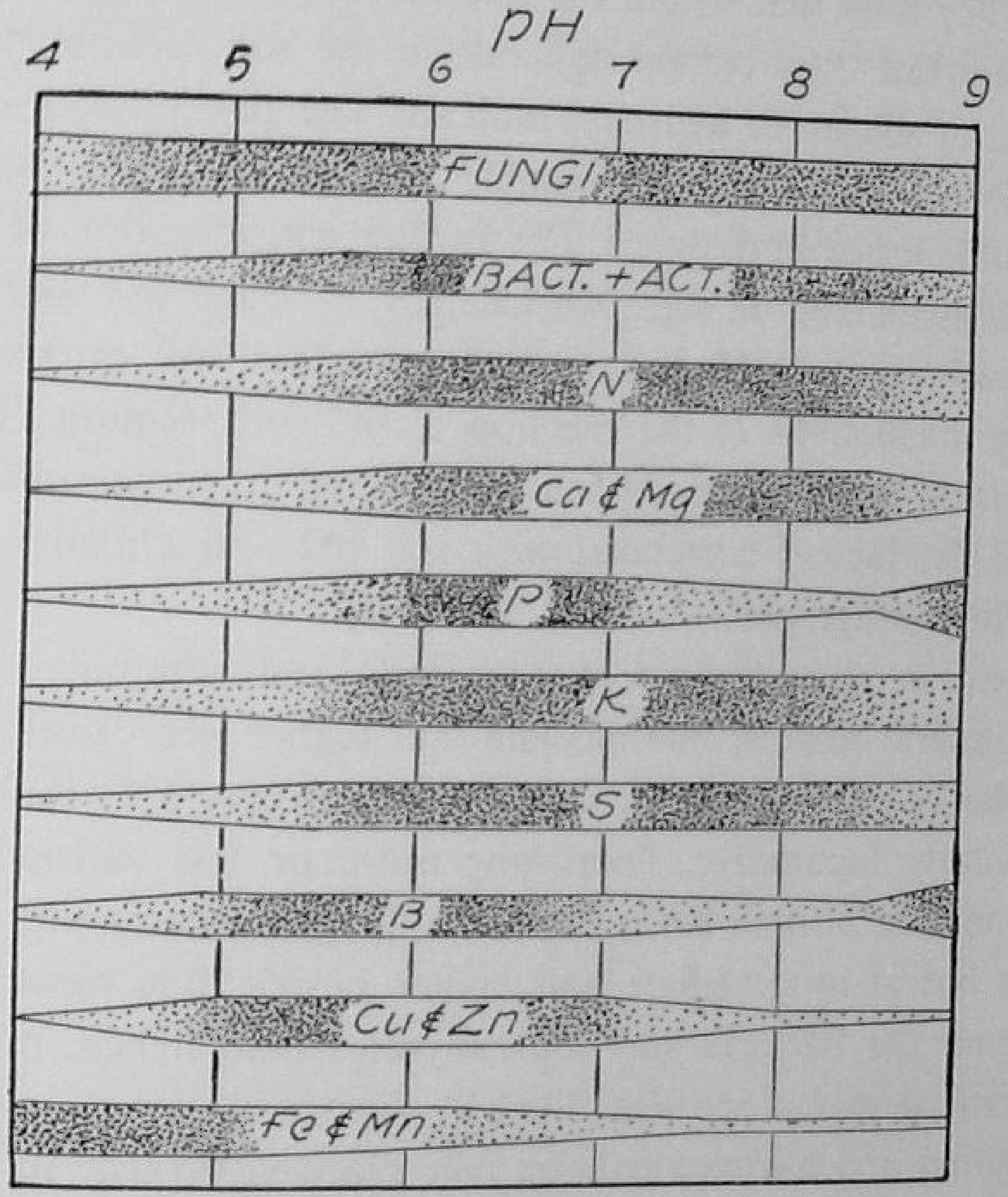

FIG. 14:4. *Diagram showing the relationships existing in mineral soils between pH on the one hand and the activity of microorganisms and the availability of plant nutrients on the other. The width of the bands and the degree of shading indicates the zones of greatest microbial activity and most ready availability of nutrients.*

Apparently the availability of nitrogen depends in large degree upon the activity of microorganisms and the mobility of calcium and magnesium. Note that the satisfactory availability of phosphorus is restricted to a pH range of approximately 6 to 7. The wide ranges for potassium and sulfur are noticeably in contrast with that of the phosphorus. Also it is evident that the soil must be somewhat acid, say pH 6, if the trace elements, even if present in suitable amounts, are to show satisfactory availability.

Considering the correlations as a whole, a pH range of approximately 6 or 7 seems to promote the most ready availability of plant nutrients. In short if soil pH is suitably adjusted for phosphorus, other plant nutrients, if present in adequate amounts, will be satisfactorily available in most cases.

acid currently supplied by the application of superphosphate or other fertilizers carrying phosphorus.[17]

Some authorities are satisfied that the diminution in phosphorus fixation by iron, aluminum, manganese, and calcium fully accounts for the greater availability of this nutrient to higher plants within the pH limits specified. Other investigators contend that still another phenomenon is involved. They hold that within the intermediate pH range the phosphate ions are adsorbed [18] by certain minerals in the soil, possibly through the replacement of silicate or hydroxyl radicals. The phosphate-ions thus held are considered to be slowly available to higher plants and to suffer only negligible losses in drainage. For further consideration of phosphorus fixation and availability in soils, see Chapter 17, page 481 and ff.

Soil organisms and pH. It is well known that soil organisms are influenced by fluctuations in the reaction of the soil solution. This may be due in extreme cases to the H ion itself [19] but in most soils it must be ascribed to the factors correlated with soil pH and already discussed in the preceding paragraphs.

In general, it is recognized that bacteria and actinomycetes function better in mineral soils at intermediate and higher pH values, the activity being markedly curtailed when the pH drops below 5.5. Fungi, however, are particularly facultative, flourishing more or less satisfactorily at all soil reactions. In normal soils, therefore, fungi predominate at the lower pH values but at intermediate and higher ranges they meet strong competition from the bacteria and actinomycetes and, hence, must yield the field to some degree. (See Fig. 14:4.)

Nitrification and nitrogen fixation take place vigorously in mineral soils only at pH values well above 5.5. However, decay, aminization, and

[17] Stanford, G., C. McAuliffe, and R. Bradfield, "The Effectiveness of Superphosphate Top-dressed on Established Meadows," *Agronomy Journal*, 42: 423–426, 1950.

[18] See Bradfield, Richard, George Scarseth, and J. G. Steele, "Factors Affecting the Retention of Phosphates by Clays," *Trans. 3rd Internat. Cong. Soil Sci.*, I: 74–75, 1935. Also, Midgley, A. R., "Phosphate Fixation in Soils—A Critical Review," *Proc. Soil Sci. Soc. Amer.*, 5: 24–30, 1940; and Metzger, W. H., "Phosphorus Fixation in Relation to the Iron and Aluminum of the Soil," *Jour. Amer. Soc. Agron.*, 33: 1093–1099, 1941.

[19] It is suggested by McCalla that H-ions are harmful to microorganisms not lethally but because they are so strongly adsorbed at the cell interfaces. Since H ions are displaced with difficulty by other cations, they may hold their position so tenaciously as to prevent the organisms from obtaining, through ionic exchange, satisfactory amounts of the cationic nutrients. See McCalla, T. M., "Why Does H+ Become Toxic to Soil Bacteria," *Proc. Soil Sci. Soc. Amer.*, 6: 165–167, 1941.

ammonification, although curtailed, will still proceed with considerable intensity at lower pH values because most fungi are able to effect these enzymic transfers at high acidities. This is, indeed, fortunate since higher plants growing on very acid soils are provided with at least ammoniacal nitrogen.

All in all, a soil in the intermediate pH range, say from 6 to 7, perhaps presents the most satisfactory biological regime. Here nutrient conditions are favorable without being extreme and phosphorus availability is at a maximum.

One very significant exception to the generalized correlation of bacteria with soil reaction should be mentioned. The organisms that oxidize sulfur to sulfuric acid (page 156) seem to be markedly facultative. Apparently they not only function vigorously in soils at medium to higher pH values but under markedly acid conditions as well. This is extremely important as it is therefore possible to apply sulfur to soils and develop, through the activity of these bacteria, highly acid conditions. If these organisms were at all sensitive to low pH and its correlated factors, their activity would soon be retarded and finally brought to a halt by their own acidic products. Under such conditions sulfur would be relatively ineffective as a soil acidifier.

14:10. THE RELATION OF HIGHER PLANTS TO SOIL REACTION

On the basis of the preceding correlations it is possible to distinguish, more or less clearly, three physiological setups in respect to arable soils: (1) the conditions presented by a very acid soil, (2) those of a mildly alkaline soil, and (3) the physiological complex of a soil intermediate in reaction.

A very acid soil will, of course, present a low pH, (say 4.5), with low exchangeable calcium and magnesium, and a high solubility of aluminum, iron, manganese and boron. Besides there is the possibility of organic toxins and certainly there will be a low availability of nitrogen and phosphorus. (See Fig. 14:4.)

At the other extreme will be an arable alkaline soil with a pH perhaps of 7.5. Here will be found plenty of active calcium and magnesium, little or no toxic aluminum, a mild yet active humus, and a ready availability of nitrogen. However, if the pH is too high, an inadequate availability of

iron, manganese, copper, zinc and especially of phosphorus and boron may occur.

The third and intermediate physiological setup is presented by a moderately to slightly acid soil. This seems for the average plant to be quite satisfactory since the chemical and biological agencies are well in balance. Nutrient availability and microorganism activity seems to be most satisfactory under these conditions. (See Fig. 14:4.)

Because of the many physiological factors involved, it is very difficult to correlate with any exactitude the optimum growth of plants on mineral soils with their pH. On the other hand, the relationship of higher plants to the three physiological setups described above can be established and in a practical way are just as significant. On this basis some of the important plants are tentatively rated. (See Fig. 14:5.)

Crop ratings. With such crops as alfalfa and sweet clover abundant, calcium seems to be a very important factor.[20] These plants are calcium-loving and are adjusted to the physiological conditions of a high-lime soil. Except under especially favorable conditions, humid-region mineral soils must, sooner or later, be limed in order to grow crops of this group satisfactorily.

Native rhododendrons and azaleas are at the other end of the scale and apparently require a considerable amount of iron. This constituent is copiously available only at low pH values and consequently at low percentage base saturations. Undoubtedly highly acid soils also present other conditions physiologically favorable for this type of plants. Incidentally, soluble aluminum apparently is not detrimental as it is to certain plants higher up the scale. If the pH and the percentage base saturation are not low enough, plants of the low-lime type will show chlorosis and other symptoms indicative of an unsatisfactory nutritive condition.

As arable soils in a humid region are usually somewhat acid, it is indeed fortunate that most cultivated crop plants not only grow well on moderately to slightly acid soils but seem to prefer the physiological conditions therein. (See Fig. 14:5.) Since pasture grasses, many legumes, small grains, intertilled field crops, and a large number of vegetables are included in this broadly tolerant group, soil acidity is not such a calamity as it was once considered. In terms of pH, a range from 5.8 or 6.0 to slightly above 7.0 is most suitable for this group. The significance of this as it relates to liming is presented in Chapter 15, page 442.

[20] *Soil Sci.*, Vol. 65, No. 1, Jan. 1948, carries a symposium of eleven articles on calcium. Several bear on the phases under consideration.

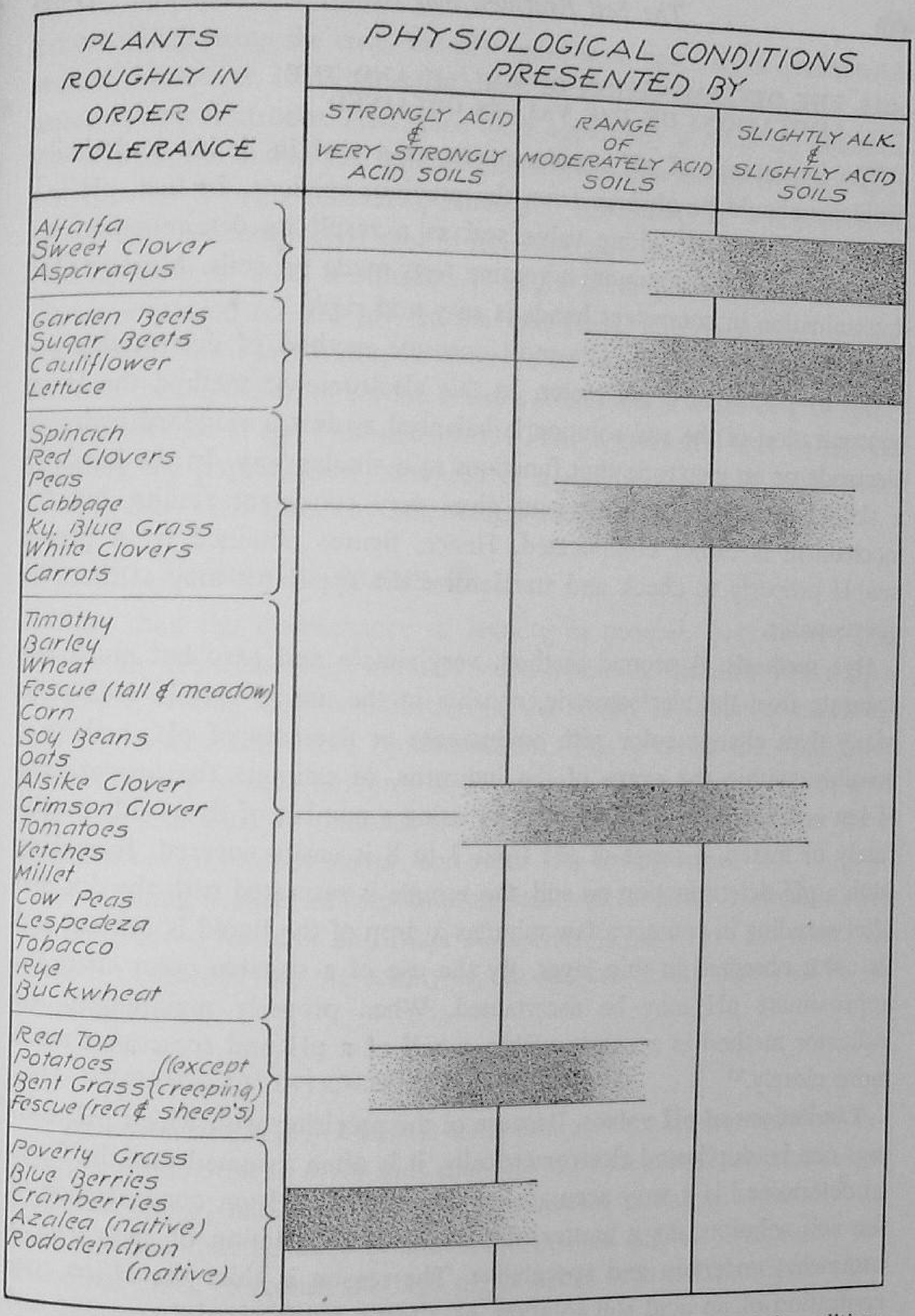

FIG. 14:5. *Diagram showing the relation of higher plants to the physiological conditions presented by mineral soils of different reactions. Note that the correlations are very broad and are based on pH ranges. The fertility level will have much to do with what the relationship shall be in specific cases. Such a chart is of great value in deciding whether or not to add lime and the rate of application if any.*

14:11. THE DETERMINATION OF SOIL pH AND THE LIMITATIONS OF THE VALUES OBTAINED

The importance of pH measurements as a tool in liming and similar problems should be obvious from the previous sections. In fact, pH is a diagnostic figure of unique value and as a result its determination has become one of the commonest routine tests made on soils. Moreover, its determination in competent hands is easy and rapid.

Electrometric method. The most accurate method of determining soil pH is by means of a pH meter. In this electrometric method the H-ion concentration of the soil solution is balanced against a standard hydrogen electrode or an electrode that functions in a similar way. In the hands of a skilled operator the instrument gives very consistent results, but the mechanism is rather complicated. Hence, figures obtained by a person unable properly to check and standardize the apparatus may at times be questionable.

Dye methods. A second method, very simple and easy but much less accurate than the electrometric, consists in the use of certain *indicators.* Many dyes change color with an increase or decrease of pH, making it possible, within the range of the indicator, to estimate the approximate H-ion concentration of a solution. By using a number of dyes, either separately or mixed, a range of pH from 3 to 8 is easily covered. In making such a pH determination on soil, the sample is saturated with the dye and after standing in contact a few minutes a drop of the liquid is run out and its color observed in thin layer. By the use of a suitable color chart the approximate pH may be ascertained. When properly manipulated the indicator method is accurate within a half of a pH and sometimes much more closely.[21]

Limitations of pH values. Because of the precision with which pH readings can be duplicated electrometrically, it is often assumed that the figure so determined is a very accurate indication of the H-ion concentration of the soil solution. As a matter of fact, the interpretation of such data is somewhat uncertain and speculative. The reason is this: the H-ion concentration of an acid soil solution, as already emphasized (page 395 and Fig. 14:1), is markedly heterogeneous. It ranges from a low acidity at the surface of the capillary films to a very high acidity near the colloidal in-

[21] For a comparison of the different dye tests, see Mason, D. D., and S. S. Obenshain, "A Comparison of Methods for the Determination of Soil Reaction," *Proc. Soil Sci. Soc. Amer.*, 3: 129–137, 1938.

terfaces. Such being the case, the pH figure is at best only a questionable average. Moreover, it is uncertain how much of the active H ions is compassed by the electrodes. And since there apparently is no sharp demarcation between the active and potential acidities, a new doubt is raised as to exactly what is being measured. Thus, the colloidality of a soil prevents an accurate estimate of its real H-ion concentration.[22]

In the light of such a situation it might seem peculiar that so much reliance is placed on soil pH. In the first place, it is easily and quickly determined. More important, however, is its susceptibility, in spite of its apparent inadequacies, to certain broad correlations that are of great practical significance (Figs. 14:4 and 14:5). Thus, a great deal may be inferred regarding the physiological condition of a soil from its pH value; much more, in fact, than from any other single analytical datum.

14:12. SOIL ACIDITY PROBLEMS

Other than the maintenance of fertility in general, two distinct procedures are often necessary on acid soils, especially those at intermediate pH values. One is the intensification of the acidity in order to encourage such plants as azaleas and rhododendrons. The other is the application of lime, usually in such amounts as to raise the pH at least to 6.0 or even to 6.5 or 7.0. This so modifies the physiological conditions as to favor alfalfa, sweet clover, red clover, and other lime-loving crops.

Since liming is such an important agricultural feature, its consideration will be reserved for later and fuller discussion (Chap. 15). However, the methods of intensifying the acidity of the soil are briefly discussed in the following section.

14:13. METHODS OF INTENSIFYING SOIL ACIDITY

A reduction of the pH of soils is often desirable for several reasons. For example, this is done to favor such plants as rhododendrons and azaleas, as suggested above, and also to discourage certain diseases, especially the actinomycetes that produce potato scab. In arid regions treatments are sometimes made to reduce the high pH of alkali soils sufficiently to allow common field plants to grow. (See page 417.)

[22] Chapman, H. D., J. H. Axley, and D. S. Curtis, "The Determination of pH at Soil Moisture Contents Approximating Field Conditions," *Proc. Soil Sci. Soc. Amer.*, 5: 191–200, 1940.

Mattson, S., and L. Wiklander, "The Laws of Soil Colloidal Behavior: XXI B. The Amphoteric Points, the pH and the Donnan Equilibrium," *Soil Sci.*, 49: 150, 1940.

Acid organic matter. When dealing with ornamental plants mentioned above, acid organic matter may be mixed with the soil already at hand to lower the pH of the latter. Leafmold, pine needles, tanbark, sawdust, and moss peat, if highly acid, are quite satisfactory in preparing such a compost. Farm manure, however, may be alkaline and consequently should be used with caution for the purpose under consideration.

Use of chemicals. When the above methods are not feasible, chemicals may be used. For rhododendron, azaleas, and other plants that require considerable iron, *ferrous sulfate* [23] is sometimes recommended. This salt by hydrolysis develops sulfuric acid which drastically lowers the pH and liberates some of the iron already present in the soil. At the same time soluble and available iron is being added. Such a chemical thus serves a double purpose in effecting a change in the physiological condition of a soil.

Another material that is even better in some respects is *flowers of sulfur*. This usually undergoes vigorous microbial oxidation in the soil (see page 407) and under favorable conditions is four or five times more effective pound for pound in developing acidity than is ferrous sulfate. Moreover, it is comparatively inexpensive, easy to obtain, and is a material often used for other purposes on the farm.

No definite recommendation can be made as to the amounts of ferrous sulfate or of sulfur that should be applied, since the buffering of soils and their original pH are so variable. With composted soils to be used in greenhouses, in nurseries, and around ornamental plants, the best way is to make several preliminary treatments using different amounts of the amendments with definite increments of the soil. After incubating at optimum temperature and moisture for several weeks, pH determinations may be made and a tentative decision arrived at as to the amounts of ferrous sulfate or sulfur that probably would give the desired results.

For rhododendrons and azaleas 1 to 2 pounds of sulfur per 100 square feet for each half a pH that the soil is to be lowered, is perhaps not too much. The dosage must, of course, be varied according to the texture of the soil and its organic content. In any case the sulfur should be well mixed with the surface soil.

[23] Aluminum sulfate will acidify soil just as satisfactorily as the ferrous sulfate but it carries no iron. Moreover, the aluminum thereby introduced may be toxic to plants that might later occupy the soil.

Control of potato scab. Sulfur is also effective in the control of potato scab since the actinomycetes that cause it are discouraged by acidity. Ordinarily when the pH is lowered to 5.5, or perhaps better to 5.3, their virulence is much reduced. In using sulfur to thus increase soil acidity the management of the land, and especially the rotation, should be such that succeeding crops are not unfavorably affected.

For the control of potato scab the amount of sulfur, applied in the row, varies from 100 to 300 pounds to the acre, depending on circumstances. Experience and good judgment are the major factors in such a decision. The results, both on the pH and the crop, should be checked and the applications made in succeeding years changed to conform with the influence exerted by the previous dosage.

14:14. REACTION OF ZONAL SOILS OF ARID REGIONS

Arid region zonal soils occur in areas where the rainfall is seldom more than 20 inches yearly and usually is much less. Lack of extensive leaching leaves the base status of these soils high. In fact, a fully and normally developed zonal profile usually carries at some point in its profile (usually in the C horizon) a calcium carbonate accumulation greater than that of its parent material. The lower the rainfall the nearer the surface this layer will be. (See Fig. 12:7.)

As a result these soils may have alkaline subsoils and alkaline or neutral surface layers. When enough leaching has occurred to free the solum of calcium carbonate, a mild acidity may then develop in the surface horizons. Such a situation exists in the case of the chernozems. The genetic classification of zonal soils of arid regions with a pertinent description of each group, has already been presented (page 349 and ff.).

14:15. REACTION OF SALINE AND ALKALI SOILS

When the drainage of arid region soils is impeded and the surface evaporation becomes excessive, soluble salts tend to accumulate in the surface horizon. Such intrazonal soils are designated as *halomorphic* (see page 353) and have been classified [24] under three heads: *Saline, Saline-Alkali,* and *Nonsaline-Alkali.*

[24] Richards, L. A. (Ed.), *Diagnosis and Improvement of Saline and Alkali Soils*, U. S. Regional Salinity Lab., 1947.

Saline soils.[25] These soils contain a concentration of neutral soluble salts sufficient to seriously interfere with the growth of most plants. Less than 15 per cent of the cation exchange capacity of these soils is occupied by sodium ions and the pH usually is below 8.5. This is because the soluble salts present are mostly neutral and, due to their domination, there is only a small amount of exchangeable sodium present.

Such soils are included among those designated by Hilgard[26] as *white alkali* soils because a surface incrustration, if present, is light in color (see Fig. 14:6). The excess soluble salts, which are mostly chlorides and sulfates of sodium, calcium and magnesium, can readily be leached out of these soils with no appreciable rise in pH. This is a very important practical consideration in the management of these soils.

FIG. 14:6. *A close-up photo showing the white salt crust on a saline soil from Colorado. The white salts are in contrast with the darker colored soil (left foreground) underneath. (Scale in inches is shown at bottom of photo.)*

Saline-alkali soils. This group contains appreciable quantities of neutral soluble salts and enough adsorbed Na-ions to seriously affect plants. Yet,

[25] *Salinization* is the term used in reference to the natural processes that result in the accumulation of neutral soluble salts in soils.
[26] Hilgard, E. W., *Soils,* The Macmillan Company, New York, 1911, p. 441.

although more than 15 per cent of the total exchange capacity of these soils is occupied by sodium, their pH, surprisingly enough, is likely to be below 8.5. This is because of the repressive influence of the neutral soluble salts, just as in the case of saline soils described above.

But unlike these soils, leaching will markedly raise the pH of saline-alkali soils.[27] This is because the exchangeable sodium, once the neutral soluble salts are removed, readily hydrolyzes and thereby markedly increases the OH-ion concentration of the soil solution. In practice this is unfortunate as the now active Na-ions disperse the mineral colloids which then develop a tight, impervious soil structure. At the same time sodium toxicity to plants is noticeably augmented.

Nonsaline-alkali soils.[28] These soils do not contain any great amount of neutral soluble salts, the detrimental effects on plants being largely due to the toxicity of the sodium as well as of the OH-ions.[29] The exchangeable sodium, which occupies decidedly more than 15 per cent of the total exchange capacity of these soils, is free to hydrolyze, because the concentration of neutral soluble salts is rather low. Consequently, the pH is above 8.5, often rising as high as 10.0. Due to the deflocculating influence of the sodium, such soils usually are in an unsatisfactory physical condition. As already stated, the leaching of a saline-alkali soil will readily change it to a characteristic alkali soil.

Because of the extreme alkalinity resulting from the Na_2CO_3 present, the surface of alkali soils usually is discolored by the dispersed humus carried upward by the capillary water—hence the name *black alkali* is frequently used. These soils are often located in small areas called *slick spots* surrounded by soils that are quite productive.

[27] This change may not occur, however, if the salts in the saline-alkali soils are mostly those of calcium and magnesium, or if the water used in irrigation contains large amounts of these cations.

[28] *Alkalinization* refers to the natural processes that give rise to soils with an undue accumulation of exchangeable sodium and a very high pH.

[29] The high pH is largely due to the hydrolysis of sodium carbonate which occurs as follows:

$$2\,Na^+ + CO_3^= + 2H_2O \rightleftharpoons 2\,Na^+ + 2\,OH^- + H_2CO_3$$

The OH ions resulting give pH values of 10 and above. Also, the sodium complex undergoes hydrolysis as follows:

$$Na\boxed{\quad Micelle \quad} + HOH \rightleftharpoons H\boxed{\quad Micelle \quad} + Na^+ + OH^-$$

14:16. GROWTH OF PLANTS ON HALOMORPHIC SOILS[30]

Saline and Saline-alkali soils with their relatively low pH (usually less than 8.5) detrimentally influence plants largely because of their high soluble salt concentration. (See Fig. 8:5, page 238.) It is common knowledge that when a water solution containing a relatively large amount of dissolved salts is brought into contact with a plant cell it will cause a shrinkage of the protoplasmic lining. This action, called *plasmolysis,* increases with the concentration of the salt solution. The phenomenon is due to the osmotic movement of the water, which passes from the cell towards the more concentrated soil solution. The cell then collapses. The nature of the salt, the species and even the individuality of the plant, as well as other factors, determine the concentration at which the individual succumbs. The adverse physical condition, especially of saline-alkali soils, may be a factor also.

Alkali soils, dominated as they are by active sodium, exert a detrimental effect on plants in three ways: (1) caustic influence of the high alkalinity induced by the sodium carbonate and bicarbonate, (2) toxicity of the bicarbonate and other anions, and (3) the adverse effects of the active sodium ions on plant metabolism and nutrition. As already suggested, the removal of the neutral salts from a saline-alkali soil will raise its pH and increase the activity of its adsorbed sodium to the point where it affects plants in the ways already described for alkali soils.

14:17. TOLERANCE OF HIGHER PLANTS TO HALOMORPHIC SOILS

The capacity of higher plants to grow satisfactorily on salty soils depends on a number of interrelated factors. The physiological constitution of the plant, its stage of growth, and its rooting habits certainly are a part of the picture.[31] In respect to the soil we must consider the nature of the various salts, their proportionate amounts, their total concentration, and their distribution in the solum. The structure of the soil and its drainage and aeration are also of moment.

[30] Hayward, H. E., and C. H. Wadleigh, "Plant Growth on Saline and Alkali Soils," *Advantages in Agronomy,* Vol. 1: 1–35, A. G. Norman, ed., Academic Press Inc., New York, 1949. This article carries a good bibliography.

[31] It is interesting to note that old alfalfa is more tolerant than young alfalfa and that deep rooted legumes show a greater resistance than those with shallow rootage.

As a result, it is difficult to forecast accurately the tolerance of crops. Only carefully controlled trials will answer this question and even then with no great degree of certainty. Perhaps the best comparative data are those presented by Richards [32] (see Table 14:1), who stipulates that tolerance shall mean the ability to produce fairly satisfactory crop yields. (See Fig. 8:5, page 238, for a view of a "white alkali" spot in a field of alfalfa.)

Table 14:1. Relative Tolerance of Certain Plants to Salty Soils. The Placings are More or Less Tentative Due to the Number of Complicating Factors Involved.

High Tolerance	*Medium Tolerance*	*Low Tolerance*
Alkali sacation	Alfalfa	Alsike clover
Bermuda grass	Barley	Apples
Canadian wild rye	Birdsfoot trefoil	Cabbage
Cotton	Carrots	Celery
Date palm	Figs	Ladino clover
Garden pea	Grapes	Lemon
Kale	Lettuce	Orange
Milo	Oats	Peach
Rape	Olives	Pear
Rescue grass	Onions	Peas
Rhodes grass	Rye	Plum
Salt grass	Sweet clover	Potatoes
Sugar beets	Sudan grass	Red clover
Western wheat grass	Tomatoes	White clover

14:18. MANAGEMENT OF SALINE AND ALKALI SOILS [33]

Ordinarily there are three general ways in which saline and alkali lands may be handled in order to avoid, at least partially, the injurious effects to plants. The first of these is *eradication;* the second is a *conversion* of some of the salts to less injurious forms; while the third may be designated as *control*. In the first two methods an attempt is made actually to eliminate by various means some of the salts or to render them less toxic.

[32] Richards, L. A., *Diagnosis and Improvement of Saline and Alkali Soils,* U. S. Regional Salinity Laboratory, 1947.

[33] The agricultural experiment stations of those states having salty soils have published bulletins relating to their practical management. As to books on the subject, see Thorne, D. W., and H. B. Peterson, *Irrigated Soils,* The Blakiston Company, Philadelphia and Toronto, 1949, and Kelley, W. P., *Alkali Soils, Their Formation Properties & Reclamation,* Reinhold Publishing Co., New York, 1951.

Also consult *Diagnosis and Improvement of Saline and Alkali Soils,* L. A. Richards, Editor, U. S. Regional Salinity Laboratory, Riverside, California, July 1947.

In the third, soil-management procedures are employed which keep the salts so well distributed throughout the soil solum that there is no toxic concentration within the root zone.

Eradication. Of the methods used to free the soil, at least partially, of excess salts, the commonest are: (1) underdrainage, (2) leaching or flushing, and (3) scraping. A combination of the first two, flooding after tile drains have been installed, is the most thorough and satisfactory. When this method is used in irrigated regions, heavy and repeated applications of water can be made. The salts that become soluble are leached from the solum and are drained off through the tile. The irrigation water used must, of course, be relatively free of silt and salts, especially those containing sodium.

The leaching method works especially well with pervious saline soils whose soluble salts are largely neutral and high in calcium and magnesium. Of course, little exchangeable sodium should be present. On the other hand, merely treating certain alkali and saline-alkali soils with water may intensify their alkalinity because of the removal of the neutral soluble salts. This allows an increase in the percent sodium saturation, thereby increasing the concentration of OH-ions in the soil solution. This may be avoided, as explained below, by converting the toxic sodium carbonate and bicarbonate to sodium sulfate by first treating the soil with heavy applications of gypsum or sulfur. (For reaction see page 419.) Leaching will then render the soil more satisfactory for crops.

Removal by scraping off the alkali incrustations that have accumulated at the surface is sometimes resorted to. It is never very effective, however, as large quantities of salts still remain in the soil. Land carrying enough alkali to require this procedure is usually so heavily charged that any type of reclamation is more or less unsatisfactory.

Conversion.[34] The use of gypsum on alkali land, as already suggested, is often recommended for the purpose of changing part of the caustic alkali carbonates into sulfates. Several tons of gypsum an acre are usually necessary. The soil must be kept moist, in order to hasten the reaction, and the gypsum should be cultivated into the surface, not plowed under. The treatment may be supplemented later by a thorough leaching of the soil with irrigation water in order to free it of some of its sodium sulfate.

[34] Hibbard, P. L., "Sulfur for Neutralizing Alkali Soil," *Soil Sci.*, 11: 385–387, 1921.

Kelley, W. P., and A. Aarny, "The Chemical Effect of Gypsum, Sulfur, Iron Sulfate, and Alum on Alkali Soils," *Hilgardia*, 3, No. 14, 1928.

The gypsum reacts with both the Na_2CO_3 and the adsorbed sodium as follows:

$$Na_2CO_3 + CaSO_4 \rightleftharpoons CaCO_3 + \underset{\text{leachable}}{Na_2SO_4\downarrow}$$

$$\begin{matrix} Na \\ Na \end{matrix}\boxed{\text{Micelle}} + CaSO_4 \rightleftharpoons Ca\boxed{\text{Micelle}} + \underset{\text{leachable}}{Na_2SO_4\downarrow}$$

It is also recognized that sulfur can be used to advantage on salty lands, especially where sodium carbonate abounds. The sulfur upon oxidation yields sulfuric acid which not only changes the sodium carbonate to the less harmful sulfate but also tends to reduce the intense alkalinity. The reactions of the sulfuric acid with the compounds containing sodium may be shown as follows:

$$Na_2CO_3 + H_2SO_4 \rightleftharpoons CO_2 + H_2O + \underset{\text{leachable}}{Na_2SO_4\downarrow}$$

$$\begin{matrix} Na \\ Na \end{matrix}\boxed{\text{Micelle}} + H_2SO_4 \rightleftharpoons \begin{matrix} H \\ H \end{matrix}\boxed{\text{Micelle}} + \underset{\text{leachable}}{Na_2SO_4\downarrow}$$

It is to be noted that not only is the sodium carbonate changed to sodium sulfate, a mild neutral salt, but the carbonate radical is entirely eliminated. When gypsum is used, however, the carbonate remains as a calcium salt.

Control. The retardation of evaporation is, of course, an important feature of salty soil control. The intensive use of the soil mulch is, therefore, very desirable. Such a method of soil management not only may save moisture, but also may retard the translocation upward of soluble salts into the root zone.

It is needless to say that, where irrigation is practiced, an excess of water should be avoided unless an attempt is being made to free the soil of soluble salts. Frequent light irrigations are often necessary, however, to keep the salts sufficiently dilute to allow normal plant growth.

The timing of irrigation is extremely important on salty soils, particularly during the spring planting season. Since young seedlings are especially sensitive to salts, irrigation often precedes or follows planting to move the salts downward. After the plants are well established, their salt tolerance often is somewhat greater.

The use of salt-resistant crops is another important feature of the successful management of saline and alkali lands. Sugar beets, cotton,

sorghum, barley, rye, sweet clover, and alfalfa are especially to be recommended. (See Table 14:1.) Moreover, a temporary alleviation of alkali will allow less-resistant crops to be established. Farm manure is especially useful in such an attempt. A crop, such as alfalfa, once it is growing vigorously, may maintain itself in spite of the salt concentrations that may develop later. The root action of tolerant plants is especially helpful in improving alkali soils which have a poor physical condition.

14:19. CONCLUSION

Although the discussion closes with pertinent suggestions regarding the management of saline and alkali soils, it must not be forgotten that the major theme of this chapter is *soil reaction* or, if you will, soil pH. And it is not difficult to see that as many, or even more, features of practical concern stem from soil reaction as from any other single soil characteristic. Material in the chapters that follow will emphasize this point even more decisively.

CHAPTER

15

Lime and Its Soil-Plant Relationships[1]

IT IS generally agreed that soil acidity and the physiological conditions that accompany it result from a lack of exchangeable metallic cations. The quantity of these adsorbed cations control the percentage base saturation and thereby indirectly determines the H-ion concentration of the soil solution. Consequently, a rectification of the adverse physiological setup of an acid soil is logically attained by adding suitable quantities of certain compounds carrying one or more of these necessary metals. This narrows the problem, therefore, to that of choosing the compounds that will most suitably do the job.

15:1. COMPOUNDS SUITABLE FOR THE REDUCTION OF SOIL ACIDITY

The compounds chosen to supply these metallic cations must possess certain characteristics if their usage is to be practical. For example, these materials must be cheap and abundant and in reacting with the soil they should definitely reduce the H-ion concentration. Moreover, they must not

[1] The following articles bear on the soil-plant phases of lime:

Albrecht, W. A., "Calcium-Potassium-Phosphorus Relation as a Possible Factor in Ecological Array of Plants," *Jour. Amer. Soc. Agron.*, 32: 411–418, 1940.

Pierre, W. H., and W. H. Allaway, "Calcium in the Soil, II. Biological Relations," *Proc. Soil Sci. Soc. Amer.*, 6: 16–26, 1941.

Midgley, A. R., "Lime—Its Importance and Efficient Use on Soils," *Proc. Soil Sci. Soc. Amer.*, 8: 329–333, 1943.

Pohlman, G. G., "Effect of Liming Different Soil Layers on Yield of Alfalfa and on Root Development and Nodulation," *Soil Sci.*, 62: 255–266, 1946.

Soil Sci., Vol. 65, No. 1, Jan., 1948, carries a symposium of articles on calcium, as does *Soil Sci.*, Vol. 73, No. 1, Jan., 1952. Many of these articles bear on the phase under consideration.

be too caustic to handle nor should their reaction with the soil be too rapid. Also the metallic cations supplied should encourage the aggregation of the soil colloids and should not leach from the soil too easily.

Potassium and sodium compounds. Such demands tend to eliminate the use of potassium and sodium compounds for the control of soil acidity. Both of these elements, particularly potassium, are relatively expensive. They are rather easily leached from soils and their carbonates are quite caustic to handle and are very drastic in action. In addition, the sodium compounds tend to disperse the soil colloids leaving an undesirable physical condition. Moreover, sodium and potassium are not the metallic cations that normally dominate the colloid complexes, especially those of humid region soils.

Calcium and magnesium compounds. The two metallic cations best suited for the alleviation of soil acidity are calcium and magnesium. A glance at the desired characteristics above show that these elements, especially calcium, fit the requirements more or less perfectly. They are cheap and plentiful and have favorable effects on the physical condition of soils. Moreover, their carbonates and even their oxides and hydroxides are comparatively mild and easy to handle. In humid region soils calcium and, to a lesser extent, magnesium are the metallic cations that, together with H-ions, normally predominate in the colloidal complexes. (See page 83.) It is only natural, therefore, that on acid soils attempts are made to increase their concentration by artificial means.

The choice of these two cations, however, only partially solves the problem. The associated anion in the liming compounds must also be considered. For example, calcium and magnesium salts of strong acids are generally unsatisfactory. The reason is simple. When by cation exchange adsorbed hydrogen is replaced by the metallic cations of a salt such as $CaSO_4$, a strong acid is liberated in the soil solution. This may be shown as follows:

$$\begin{matrix}H\\H\end{matrix}\boxed{\quad\text{Micelle}\quad} + CaSO_4 \rightleftharpoons Ca\boxed{\quad\text{Micelle}\quad} + 2\ H^+ + SO_4^{=}$$

Thus, even though the amount of active calcium has been increased, the pH of the soil solution may actually be reduced. Consequently, salts such as gypsum and calcium chloride are seldom recommended as liming materials. They are used only when large amounts of calcium are desired without an increase in pH.

15:2. FORMS OF LIME

With the elimination of salts of strong acids, two satisfactory groups of calcium and magnesium compounds remain. They are (1) the salts of weak acids such as the *carbonates,* and (2) basic compounds such as the *oxides* and *hydroxides*. These compounds of calcium and magnesium are commonly referred to as *agricultural limes*[2] and have the advantage, among other things, of leaving no residue of an objectionable nature in the soil. For example, the direct action of $CaCO_3$ and CaO with soil acids may be shown, perhaps oversimplified, as follows:

$$\begin{matrix}H\\H\end{matrix}\boxed{\text{Micelle}} + CaCO_3 \rightleftharpoons Ca\boxed{\text{Micelle}} + CO_2\uparrow + H_2O$$

$$\begin{matrix}H\\H\end{matrix}\boxed{\text{Micelle}} + CaO \rightleftharpoons Ca\boxed{\text{Micelle}} + H_2O$$

Note that in both cases as the reaction goes to the right there is a neutralization or removal of H-ions from the system and an increase in exchangeable calcium. Consequently, an increase in percentage base saturation is effected while at the same time the pH of the soil solution is raised.

As is to be expected, liming materials do not appear on the market as single compounds of magnesium or calcium, nor are they by any means pure. The better grades of the oxides and hydroxides are generally used in the trades, the less pure materials have an outlet as agricultural lime. The carbonated forms of lime have a number of different sources and vary to a marked degree in purity and fineness.[3]

[2] Lime from the strictly chemical standpoint refers to one and only one compound —calcium oxide. Agriculturally, however, the term has a broader meaning. Thus used, it "includes all compounds of calcium and magnesium employed in a practical way, not only to raise the pH of an overly acid soil but especially to rectify its physiological condition." It is to be noted that the definition includes magnesium as well as calcium and that the prime objective is not merely to decrease the H-ion concentration but also to alleviate the factors associated with it.

[3] Certain other compounds of calcium may at some future time be classed as agricultural lime if their use becomes common. For instance, by-product calcium silicates ($CaSiO_3$ and Ca_2SiO_4) have been successfully used in an experimental way. When an excess of this material is applied to soils, detrimental effects to higher plants, often obtained from overdoses of calcium carbonate, are not observed. See MacIntire, W. H., *et al.*, "Nature and Liming Value of Quenched Calcium Silicate Slag," *Soil Sci.*, 50: 219–232, 1940. Some of the important articles on the subject are cited.

15:3. OXIDE OF LIME

Commercial oxide of lime is commonly spoken of as *burned lime, quick-lime,* or often simply as the *oxide.* Since it usually is a finely ground powder it commonly is marketed in paper bags. Oxide of lime is quite caustic and often rather disagreeable to handle.

The devices for producing burned lime are various, ranging from small ovens to the large cylindrical kilns of commerce. In any case the general result is the same. The limestone with which the kiln is charged is decomposed by the heat. Carbon dioxide and other gases are driven off, and the impure calcium and magnesium oxides are left behind. The essential reactions that occur when calcium carbonate and dolomite are burned are as follows:

$$CaCO_3 + \text{Heat} \longrightarrow CaO + CO_2\uparrow$$

$$CaMg(CO_3)_2 + \text{Heat} \longrightarrow CaO + MgO + 2\ CO_2\uparrow$$

The purity of burned lime, as it is sold for agricultural purposes, is variable, ranging from 85 to 98 per cent. Perhaps a purity of 95 per cent is a suitable average figure. The impurities of burned lime consist of the original impurities of the limestone, such as chert, clay, and iron compounds, etc.

A number of compounds are present in commercial oxide of lime. Calcium oxide and magnesium oxide are, of course, most prominent. With them are small amounts of the hydroxides since the oxides readily take up water from the air and slake to some extent even when bagged. Also contact with the carbon dioxide of the atmosphere will tend to produce carbonates. Besides these, there are the inert impurities already mentioned.

15:4. HYDROXIDE OF LIME

This form of lime is commonly, and of course improperly, referred to as the *hydrate.* And since it is produced by adding water to burned lime, the hydroxides that result are often spoken of as *slaked lime.* The slaking reaction is as follows:

$$\text{Impure } CaO \text{ and } MgO + 2\ H_2O \longrightarrow Ca(OH)_2 + Mg(OH)_2 + \text{Impurities}$$

Hydroxide of lime appears on the market as a white powder, highly caustic and not at all pleasant to handle. And like the oxide it requires

bagging. Representative samples generally show a purity of perhaps 95 or 96 per cent.

In order to maintain the concentration of this form of lime at a high point, the slaking often is not carried to completion. As a result, considerable amounts of the oxides are likely to remain. Moreover, hydroxide of lime carbonates rather readily.[4] This is likely to be the case if the bag is left open and the air is moist. Besides the impurities, six important lime compounds are usually present: the oxides, the hydroxides, and the carbonates of calcium and magnesium. The hydroxides, of course, greatly predominate. Due to the presence of carbonates, hydroxide of lime may effervesce, often freely, when treated with dilute hydrochloric acid.[5]

15:5. CARBONATE OF LIME

A number of lime compounds are sold under the head of commercial carbonate of lime. Of these, pulverized or ground limestone is the most common. There are also bog lime or marl, oyster shells, and precipitated carbonates. Great deposits of marl occur under peat beds (page 384), and when dredged out, dried, and crushed, make excellent lime. However, the cost usually is too high to allow successful competition with limestone. Also lime carbonates are by-products from certain industries.[6] All of these forms of lime are variable in their content of calcium and magnesium.

The two important compounds carried by limestones are *calcium carbonate* ($CaCO_3$) and *dolomite* [$CaMg(CO_3)_2$]. These occur in varying proportions. When little or no dolomite is present the limestone is spoken of as *calcic*. As the magnesium increases this grades into a *dolomite limestone* and finally, if very little calcium carbonate is present and the stone is almost entirely made up of calcium-magnesium carbonate and impurities, the term *dolomite* is used. Most of the crushed limestone on the market is calcic and dolomitic, although ground dolomite is available in certain localities.

[4] The carbonation of calcium and magnesium hydroxides occurs as follows:

$$Ca(OH)_2 + CO_2 \longrightarrow CaCO_3 + H_2O$$
$$Mg(OH)_2 + CO_2 \longrightarrow MgCO_3 + H_2O$$

[5]

$$CaCO_3 + 2\,HCl \longrightarrow CaCl_2 + H_2O + CO_2 \uparrow$$
$$MgCO_3 + 2\,HCl \longrightarrow MgCl_2 + H_2O + CO_2 \uparrow$$

[6] Before using such lime one should be sure that it carries no deleterious substances derived from its previous use.

Ground limestone, which is used to a greater extent than all other forms of lime combined, varies in purity from approximately 75 to 99 per cent. The average purity of the representative crushed limestone may be put at perhaps 94 per cent.

15:6. CHEMICAL GUARANTEE OF LIMES

Since the various forms of lime are sold on the basis of their chemical composition, the commercial guarantees in this respect become a matter of great importance. The caustic forms, that is the oxide and hydroxide, may bear composition guarantees stated in one or more of the following ways—the *conventional oxide content,* the *calcium oxide equivalent,* the *neutralizing power,* and *percentages of calcium and magnesium.* In order to facilitate the explanation and comparison of the various methods of expression, composition figures for commercial burned and hydroxide of lime are drawn together in Table 15:1.

Table 15:1. Composition of a Representative Commercial Oxide and Hydroxide of Lime Expressed in Different Ways

Forms of Lime	*Conventional Oxide Content, Percentage*	*Calcium Oxide Equivalent*	*Neutralizing Power*	*Elemental, Percentage*
Commercial oxide	CaO = 77 MgO = 18	102.0	182.1	Ca = 55.0 Mg = 10.8
Commercial hydroxide	CaO = 60 MgO = 12	76.7	136.9	Ca = 42.8 Mg = 7.2

Conventional oxides and CaO equivalent. Since the *oxide* form of expression is so commonly used, this type of guarantee is designated here as the *conventional* method. The *calcium oxide equivalent,* as the term implies, is a statement of the strength of the lime in one figure, namely, CaO. The magnesium oxide is expressed in terms of calcium oxide equivalent and this figure is added to the percentage of calcium oxide present. This may be conveniently done by means of conversion factors.[7] Thus for the

[7] In order to express one lime in chemically equivalent amounts of another, simply multiply by the appropriate factor as given below:

MgO to CaO	—	1.389
$CaCO_3$ to CaO	—	.560
CaO to $CaCO_3$	—	1.786
$MgCO_3$ to CaO	—	.664
$MgCO_3$ to $CaCO_3$	—	1.186
$MgCO_3$ to Mg	—	.288
$CaCO_3$ to Ca	—	.400
MgO to Mg	—	.602
CaO to Ca	—	.714

commercial oxide of Table 15:1, 18 per cent of MgO is equivalent to 25 per cent of CaO (18 × 1.389 = 25) and 77 + 25 = 102, the calcium oxide equivalent. This means that every 100 pounds of the impure burned lime is equivalent in neutralizing capacity to 102 pounds of *pure* calcium oxide.

Neutralizing power and elemental expression. The *neutralizing power*, as the term is arbitrarily used in respect to lime, is nothing more than a statement of its strength in terms of calcium carbonate—that is, its *$CaCO_3$ equivalent*. Thus, by multiplying by 1.786 in the case above, the calcium oxide equivalent of 102 becomes 182.1, the $CaCO_3$ equivalent. This means that every 100 pounds of the impure burned lime is equivalent in neutralizing capacity to 182.1 pounds of *pure* calcium carbonate.

The *elemental* method of expression, while not so common as the other modes of statement, is required by law in some states. It may readily be calculated from the conventional oxide guarantee. Or, if given alone, the other forms of statement may be derived from it.

Commercial caustic limes practically always carry the conventional oxide guarantee and sometimes the elemental. Thus, the amount of magnesium, as well as calcium, present is indicated. This is an important consideration. In addition, one or even both of the other forms of guarantee may be given. The latter are especially desirable as they show the strength of the lime in one figure, thus making comparisons between different brands easy.

A thorough student should be able not only to derive the above factors but also to make the conversion without them, namely by the direct use of atomic and molecular weights. The atomic weights involved are as follows: Ca = 40; Mg = 24.3; O = 12; and C = 12.

For example, we wish to express, say, 1 pound of pure MgO in chemically equivalent pounds of pure CaO. As the following reactions indicate, these two compounds, molecule per molecule, are equal in neutralizing power:

$$CaO + 2\,HCl \longrightarrow CaCl_2 + H_2O$$
$$MgO + 2\,HCl \longrightarrow MgCl_2 + H_2O$$

But the molecular weight of CaO is 56 (40 + 16) and that of MgO is 40.3 (24.3 + 16). Hence on the basis of weight it takes 56 lbs. of CaO to equal 40.3 lbs. of MgO. That is:

$$MgO : CaO :: 40.3 : 56$$

And if the pounds of CaO necessary to equal 1 pound of MgO is desired, the proportion would be:

$$40.3 : 56.0 :: 1 : x$$

solving:

$$40.3\,x = 56$$
$$x = 1.389 \text{ lbs. of CaO necessary to equal 1 lb. of Mgo}$$

Here then is a factor that can be used to express pounds, or tons or per cents, etc., of MgO in chemically equivalent quantities of CaO.

Limestone guarantees. The guarantees on ground limestone differ in two respects from those of the caustic forms of lime. Usually the separate percentages of calcium and magnesium carbonates are given. These are almost always accompanied by the percentage of *total carbonates.*[8] In addition, one or more of the other four modes of guarantee may be used. By way of illustration the six methods of expression are presented in Table 15:2 for a representative ground limestone.

Table 15:2. Composition of a Representative Commercial Ground Limestone Expressed in Different Ways

Separate Carbonates, (Per Cent)	*Total Carbonates, (Per Cent)*	*Neutralizing Power*	*Conventional Oxide, (Per Cent)*	*Calcium Oxide Equivalent*	*Elemental, (Per Cent)*
$CaCO_3$ = 80 $MgCO_3$ = 14	94	96.6	CaO = 44.80 MgO = 6.70	54.10	Ca = 32.00 Mg = 4.03

Total carbonates *vs.* neutralizing power. The total carbonate method of guarantee has many advocates because, compared to the neutralizing power, it is so simple and requires no chemical explanation. Furthermore, when the total neutralizing figure for a given limestone is higher than the total carbonates, it is usually due to the presence of dolomite in the limestone. Since this mineral reacts with the soil rather slowly (see Fig. 15:1), the advantage from the standpoint of total neutralizing power is questionable unless the lime is very finely ground. Consequently, the total carbonate method of expression is perhaps a truer indication of the comparative field value of limestones.

Those that favor the neutralizing-power method of expression stress its accuracy and the fact that it can be determined very easily and quickly. This is an important consideration in a control laboratory when many samples must be analyzed. Moreover, there is the advertising phase of the controversy. For instance, a dolomitic limestone containing 46 per cent of $CaCO_3$ and 43 per cent of $MgCO_3$ [9] has a *neutralizing power* of 97 but

[8] It is well to remember that both of these methods of guarantee are in part conventional since only part of the calcium is present as $CaCO_3$. The remainder, as well as all the magnesium, is carried by the admixed dolomite [$CaMg(CO_3)_2$]. Magnesium carbonate, as such, is usually not present.

[9] This is only a conventional method of expressing the constituents in dolomitic limestone. Actually this material is composed of a mixture of $CaCO_3$ and dolomite [$CaMg(CO_3)_2$]. (See page 425.)

its *total carbonate figure* is only 89. When competition is keen, such a difference may lead to much misunderstanding and controversy.

15:7. FINENESS GUARANTEE OF LIMESTONE

The application to the soil of two different liming materials in chemically equivalent quantities does not necessarily mean that equivalent results will be attained. This is especially true if the two materials are both pulverized limestones, since the particles contained therein are apt to be quite variable in size as well as hardness. The importance of this is apparent since it is well known that the finer the division of any material the more rapid is likely to be its solution and rate of reaction. (See Fig. 15:1.) The caustic limes usually appear on the market as almost impalpable powders; consequently their fineness is always satisfactory.

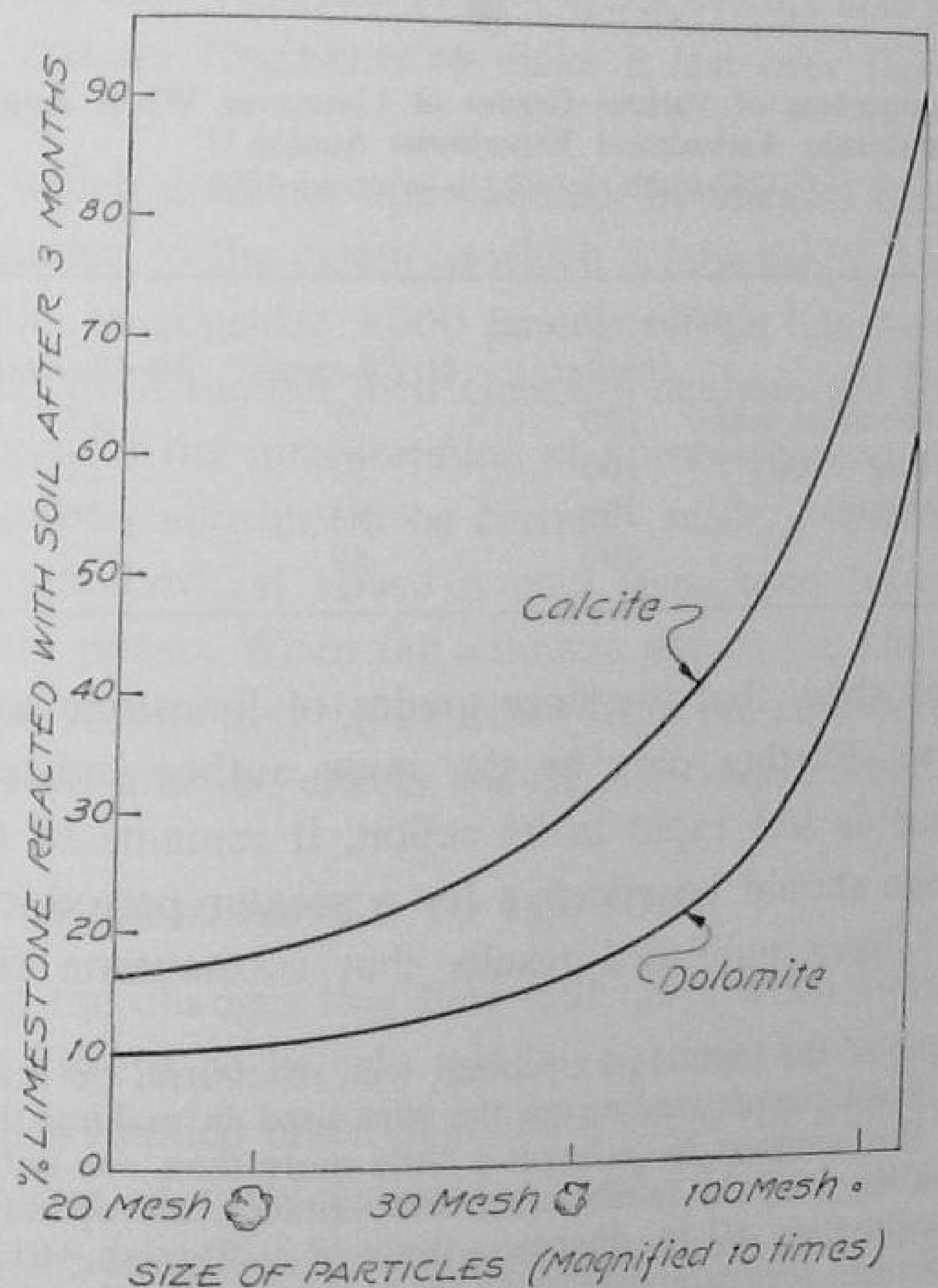

FIG. 15:1. *The relationship between particle size of calcite and dolomite respectively and the rate of reaction of these minerals with the soil. Note that calcite particles of a given size react more rapidly than do corresponding dolomite particles. The coarse fractions of both minerals neutralize the soil acidity very slowly. (These data were calculated from Schollenberger, C. J. and R. M. Salter. See footnote 12, page 430.)*

Therefore, in order to rate a limestone as to its probable effects in comparison with other limes, a *fineness guarantee* is desirable. This is usually one of the requirements of laws controlling the sale of agricultural limestone. A mechanical analysis is made by the use of screens of different mesh, a 10-mesh sieve, for example, having ten openings to the linear inch.[10] The proportion of the limestone that will pass through the various screens used constitutes the guarantee.

15:8. INTERPRETATION OF A FINENESS GUARANTEE

Before a statement can be made as to the degrees of fineness a limestone should attain to be satisfactory, some of the experimental work available on the subject should be considered. White presents the following significant data (Table 15:3) as a result of certain laboratory and greenhouse studies at State College, Pennsylvania.

Table 15:3. A Comparison of Various Grades of Limestone When Applied at the Same Rates, Pennsylvania Agricultural Experiment Station[11]
(100-mesh material is taken as 100)

Conditions	*100-mesh and smaller*	*60-80-mesh*	*20-40-mesh*	*8-12-mesh*
Solubility in carbonated water	100	57	45	28
Value in correcting acidity	100	57	27	18
Formation of nitrates	100	94	56	12
Plant growth	100	69	22	5

These figures show that the finer grades of limestone are much more rapidly effective. Further data by the same author indicate that, while the coarser lime is less rapid in its action, it remains in the soil longer and its influence should be effective for a greater period of years. Other investigators[12] have published results that substantiate the conclusions

[10] The diameter of the individual openings will, of course, be much less than 0.1 of an inch, the exact size depending on the wire used in making the sieve. Usually the diameter of the openings in inches is a little more than one-half of the quotient obtained by dividing 1 by the mesh rating. For instance, the openings of a 10-mesh screen are approximately .07 in. diameter; those of a 50-mesh, .0122 in.; and those of a 100-mesh screen, approximately .0058 in. Unfortunately there is no standardization of the sieves used for grading agricultural limestone.

[11] White, J. W., *The Value of Limestone of Different Degrees of Fineness*, Bulletin 149, Penn. Agr. Exp. Sta., 1917.

[12] Lyon, T. L., *Relative Effectiveness of Limestone Particles of Different Sizes*, Bulletin 531, Cornell Univ. Agr. Exp. Sta., 1931.

See also Schollenberger, C. J., and R. M. Salter, "A Chart for Evaluating Agricul-

above. The proportionate responses are somewhat different, however. This is to be expected, as limestones of different hardness applied to various soil types are sure to respond rather diversely.

Fine limestone. Everything considered, a pulverized limestone, *all of which will pass a 10-mesh screen, and at least 50 per cent of which will pass a 100-mesh sieve,* should give excellent results and yet be cheap enough to encourage its use. Such a lime is sufficiently pulverized to rate as a *fine* limestone.

Nevertheless, many limes are finer than this, 50 or 60 per cent sometimes passing a 200-mesh screen. However, because of the cost of grinding the stone to a very fine condition and the rapidity with which such material disappears from the soil, a medium ground lime such as specified above, seems to be a more desirable commercial product. Such material has enough of the finer particles to give quick results and yet a sufficient amount of the coarser fragments to make it last over the period of the rotation.

A limestone which does not approximate the fineness designated above should be discounted to the extent to which it falls short. It may be necessary, for example, to consider 3,000 pounds of one limestone as equal to 1 ton of another, even though their chemical analyses are the same. Considerable judgment in the interpretation of fineness guarantee is necessary in order that such an adjustment be correctly made. Much limestone that falls below the standard set above is now being used because, as a by-product, it is very cheap. When the amounts put on the land are properly adjusted, as good results may be expected from the coarser limes as from the finer limestones and the effects should last considerably longer.

15:9. CHANGES OF LIME ADDED TO THE SOIL

In considering the changes that lime undergoes when added to the soil two things must always be kept in mind: (1) that the calcium and magnesium compounds applied undergo solution under the influence of a variable partial pressure of carbon dioxide [13] and (2) that an acid colloidal complex will adsorb considerable amounts of calcium and magnesium ions.

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tural Limestone," *Jour. Amer. Soc. Agron.*, 35: 955–966, 1943. And Davis, F. L., "Effect of Fineness of Agricultural Lime upon Crop Response," *Agron. Jour.*, 43: 251–255, 1951.

[13] For a discussion of this phase see Bradfield, Richard, "Calcium of the Soil: 1. Physico-Chemical Relations," *Proc. Soil Sci. Soc. Amer.*, 6: 8–15, 1941.

Reaction with CO_2. When lime, whether the oxide, hydroxide, or the carbonate, is applied to an acid soil, the movement, as solution occurs, is toward the bicarbonate form. This is because the partial carbon dioxide pressure, usually several hundred times greater than that of the atmospheric air, generally is intense enough to prevent the existence of the hydroxide or even the carbonate. The reactions, written only for the purely calcium limes, are as follows:

$$CaO + H_2O \longrightarrow Ca(OH)_2$$
$$Ca(OH)_2 + 2\ H_2CO_3 \longrightarrow Ca(HCO_3)_2 + 2\ H_2O$$
$$CaCO_3 + H_2CO_3 \longrightarrow Ca(HCO_3)_2$$

Reaction with soil colloids. This, however, represents only the solution of the lime in carbonated water. The soil situation is not so simple as these reactions might lead one to assume. This is because the soil colloidal matter continually upsets the equilibrium tendencies by adsorbing the ions of calcium and magnesium. These ions may be taken from the soil solution proper or directly from the solid phase if the contact is sufficiently close. The adsorption in respect to calcium may be indicated as follows:

$$\begin{matrix}H\\H\end{matrix}\boxed{\text{Micelle}} + Ca(OH)_2 \rightleftharpoons Ca\boxed{\text{Micelle}} + 2\ H_2O$$

$$\begin{matrix}H\\H\end{matrix}\boxed{\text{Micelle}} + \underset{\text{(in solution)}}{Ca(HCO_3)_2} \rightleftharpoons Ca\boxed{\text{Micelle}} + 2\ H_2O + 2\ CO_2\uparrow$$

$$\begin{matrix}H\\H\end{matrix}\boxed{\text{Micelle}} + \underset{\text{(solid phase)}}{CaCO_3} \rightleftharpoons Ca\boxed{\text{Micelle}} + H_2O + CO_2\uparrow$$

As the above reactions of limestone proceed carbon dioxide is freely evolved. This explains why the application of ground limestone for a time is likely to cause an increase in the carbon dioxide partial pressure within the soil. This increase is especially important since it occurs at the interface where the solvent action of carbon dioxide is particularly effective. In addition, the adsorption of the calcium and magnesium raises the percentage base saturation of the colloidal complex and the pH of the soil solution is pushed up correspondingly. (See page 392.)

Distribution of Ca and Mg in limed soil. Calcium and magnesium, if supplied by a limestone of average fineness, will exist in the soil, at least

for a time, in three forms: (1) as solid calcium and calcium-magnesium carbonates, (2) as exchangeable bases adsorbed by the colloidal matter, and (3) as dissociated cations in the soil solution mostly in association with bicarbonate ions. When the calcium and calcium-magnesium carbonates have all dissolved the lime system, now a two-phase one, becomes somewhat simpler.

It should not be inferred from the above that there is a homogeneous distribution of calcium and magnesium through the soil solution. Far from it. In the immediate neighborhood of the coarse particles of the limestone a noticeable concentration of calcium and magnesium ions will be found. If the carbon dioxide pressure is about that of the atmospheric air, the pH around the lime particles will be near 8, perhaps a little above.

However, at the interfaces of the colloidal complex, especially if the latter has been raised to a rather high degree of base saturation, the concentration of calcium and magnesium ions, in contrast, will be very much greater. At the same time due to adsorbed hydrogen, the pH in this zone may be definitely below 7. Between these two pH extremes variable concentrations of Ca-, Mg- and H-ions will be found in the soil solution depending upon carbon dioxide pressure of the soil air and other factors. Heterogeneity in respect to the distribution of the above cations is the rule rather than the exception.

Depletion of Ca and Mg. As time goes on, not only do the particles of the added lime carbonates gradually disappear, but also the colloidal complex loses part of its bases. This is effected by H-ions generated by carbonic and other acids. In this way the so-called reserve lime, both carbonate and adsorbed, is gradually fed into the soil solution (cation exchange), there to be used in many different ways. The mechanism of these losses is fully explained on page 97.

If the soluble calcium (and magnesium) compounds are continually removed, as is the case particularly in humid regions, the percentage base saturation and pH are gradually reduced. Eventually the soil presents such an unsatisfactory physiological conditions that another application of lime is necessary. This, then, is the type of cycle through which much of the calcium and magnesium added to arable soils swings in humid regions.

15:10. LOSS OF LIME FROM ARABLE SOILS

In following calcium and magnesium through the lime cycle one cannot escape the possibilities of loss, nor the fact that these removals not only

must be large in humid regions but also must exert a drastic physiological effect on the land. Three ways of loss exist: (1) by erosion, (2) by crop removal, and (3) by leaching.

Since these three types of lime loss have already been discussed and evaluated in Chapter 9, it is a simple matter to draw such data together in tabular form (Table 15:4). Although the values cited are questionable, if considered as more or less absolute in nature, they are quite significant when used comparatively.

The data for erosion removals are for a silt loam in Missouri, cropped to a rotation of corn, wheat, and clover. (See Table 9:8.) The acre annual removal by crops was calculated for a standard and representative rotation assuming reasonable yields. (See Table 9:5.) The leaching losses are for a postulated representative silt loam under a rainfall of perhaps 36 to 40 inches and cropped to a standard farm rotation. (See Table 9:5.) All data are in pounds an acre a year expressed in the conventional *oxide* form and also in the more practical terms of *calcium* and *magnesium carbonates.*

Table 15:4. Lime Losses from Soil in Pounds per Acre per Year

Manner of Removal	*Calcium*		*Magnesium*	
	CaO	$CaCO_3$	MgO	$MgCO_3$
By erosion, Missouri experiments, 4% slope	120	214	48	100
By the average crop of a standard rotation	35	62	30	63
By leaching from a representative silt loam	125	223	25	52
Total		499		215

The greater loss of calcium than magnesium, no doubt, is due to the fact that the soil colloidal matter almost always carries a much larger amount of the former in an exchangeable condition. And, since the average lime supplies six or seven times more calcium than magnesium, this loss ratio will in general be maintained and even accentuated in arable lands as liming proceeds.

This does not mean, however, that the magnesium in lime is of minor importance. Far from it. In fact, judging from the figures of Table 15:4, there should always be at least one-third as much magnesium as calcium

in the lime applied in order to proportionately meet the outgo of the two constituents. Other things being equal, it is always wise to select a magnesium limestone.

The figures quoted in the table above indicate that 500 to 600 pounds of limestone per acre per year are none too great to meet the loss from cropped soils in humid regions. This amounts to perhaps 1 to 1.5 tons of carbonate of lime during the period of the average rotation depending upon the kind of soil and other factors. Such a conclusion, even though tentative, justifies the attention that is paid to lime in any scheme of fertility management in areas of medium to heavy rainfall.

15:11. THE EFFECTS OF LIME ON THE SOIL

It has already been emphasized that the changes of lime in the soil are many and complicated. Therefore, the discussion that follows must of necessity, rather than choice, be more or less general in nature. The better known effects of liming will be considered under three heads: (1) physical, (2) chemical, and (3) biological.

Physical effects. In heavy soils there is always a tendency for the fine particles to become too closely associated. Such a condition interferes with air and water movement and, therefore, granulation is highly desirable. A satisfactory crumb structure is somewhat encouraged in an acid soil by the addition of any form of lime, although the influence is largely indirect. For example, the effect of lime upon biotic forces are paramount, especially those that have to do with the decomposition of the soil organic matter and the synthesis of humus. The genesis of the latter as well as its persistence greatly encourages granulation. (See page 69.) In this respect the stimulating effect of lime on deep rooted plants, especially legumes, should not be ignored.

Chemical effects.[14] If a soil at pH of 5.0 is limed to a more suitable pH value (say 6.5) a number of significant chemical changes occur. Many of these were stressed in Chapter 14 and will be merely outlined here to re-emphasize their importance. For example:

(1) The concentration of H-ions will decrease.
(2) The concentration of OH-ions will increase.
(3) The solubility of iron, aluminum, and manganese will decline.
(4) The availability of natural or added phosphates will be augmented.
(5) The exchangeable calcium and magnesium will increase.

[14] *Soil Science*, 65, No. 1, Jan., 1948, carries a symposium on lime in which several articles are devoted to this phase.

The liberation of mineral nutrients, particularly potassium, by the addition of lime is somewhat uncertain although it evidently occurs, at least to some extent. The process is probably a very complicated and coordinated chemical and biological change. Consequently, the stimulation to plants by such an action is difficult to establish, since so many compensating factors are involved. For example, liming may even decrease potassium availability.[15] This has been ascribed to the stimulating influence of the lime on the microorganisms, the liberated potassium being appropriated by the vigorously multiplying soil flora. The difficulty of measuring potash release under such a condition is obvious.

Of the specific chemical effects of lime already mentioned, the reduction in acidity and the rise in pH are the ones commonly uppermost in the popular mind. The mere correction of the soil reaction, insofar as higher plants and microorganisms are concerned, is important very largely in indirect ways and these are mostly nutritional. Hence, in considering the benefits of lime, the stress should be upon the nutritional effects, both direct and indirect, rather than upon the mere change in soil pH. In fact, by drilling lime with the seed it is possible to obtain definite benefits without appreciably reducing the hydrogen-ion concentration of the whole furrow slice. It should also be recognized above all that the changes due to liming are so many, so complex, and so interrelated, that it is impossible to ascribe the influences observed to any one factor.

Biological effects. The stimulating influence of lime upon the general-purpose, heterotrophic soil organisms, thereby increasing the activity of the organic matter and nitrogen of an acid soil, is especially significant, since the rate of the turnover of these constituents often is more important than the actual amounts present. This stimulation of enzymic processes not only favors the formation of humus but also encourages the elimination of certain organic intermediate products that might be toxic to higher plants.

Most of the favorable soil organisms, as well as some of the unfavorable ones such as those that produce potato scab, are encouraged by liming.

[15] Jenny, Hans, and E. R. Shade, "The Potash-Lime Problem in Soils," *Jour. Amer. Soc. Agron.*, 26: 162–170, 1934.

See also Dean, H. C., *The Effect of Liming on the Liberation of Potassium in Some Iowa Soils*, Research Bulletin 197, Ia. Agr. Exp. Sta., 1936; Gilligan, G. M., "The Effect of Fertilizers and Lime Upon the Electro-dialyzable and Exchange Potash of Cropped Soil," *Jour. Agr. Res.*, 53: 61–65, 1936; and MacIntire, W. H., W. M. Shaw, and J. B. Young, "The Repressive Effect of Lime and Magnesia upon Soil and Subsoil Potash," *Jour. Agr. Sci.*, 20: 499–510, 1930.

Aminization, ammonification, and sulfur oxidation are markedly speeded up by active calcium. The bacteria that fix nitrogen from the air, both non-symbiotically and in the nodules of legumes, are especially stimulated by the application of lime.

Nitrification, a biological phenomenon of great importance, requires active metallic cations. When lime is inadequate, this desirable transformation will not proceed rapidly. In fact, the successful growth of most soil microorganisms so definitely depends upon lime that satisfactory biological activities cannot be expected if soils fall below a given calcium and magnesium level.

15:12. CROP RESPONSE TO LIMING

The biological effects of lime will now be extended to include higher plants, obviously a consideration of great practical concern. Much experimental work has been done in various parts of the world in determining the relative response of different crops to liming and the reason for certain well-known differences. The results, while in close agreement as to some crops, show striking disagreements as to others. This is to be expected, since the varying conditions of the tests, especially in respect to fertility levels, no doubt have had a marked influence on the response of the plants under consideration.

Specific crop needs. Figure 14:5 (page 409) specifies in a general way the lime levels at which various plants seem to grow most satisfactorily, thereby indicating whether or not a particular crop is likely to be benefited by liming. Of the lime-loving plants, alfalfa, sweet clover, red clover, asparagus, cauliflower and lettuce are representative. However, a surprisingly large proportion of our crop plants is quite tolerant to the physiological conditions presented by moderately acid soils. Such plants respond to lime, if at all, more or less indirectly due to its stimulating influence upon the legume preceding them in the rotation. And as a further examination of Figure 14:5 will show, some plants, such as cranberries and native azaleas, grow much better when the content of exchangeable calcium and magnesium of soils is exceedingly low. The chart under consideration is worthy of careful study and should be at hand when liming plans are being laid.

Reasons for response. When plants are benefited by lime, a number of possible reasons may be suggested. These are listed as follows: (1) direct nutritive or regulatory action of the calcium and magnesium; (2) removal

or neutralization of toxic compounds of either an organic or inorganic nature; (3) retardation of plant diseases; (4) an increased availability chemically of plant nutrients; and (5) an encouragement of microorganic activities favorable in a nutritive way. Since several of these factors undoubtedly function concurrently, crop response to liming is a complicated phenomenon and only the broadest conclusions may be drawn.

The growth of a number of plants is definitely retarded by liming, prominent among which are cranberries, blueberries, watermelons, laurel, and certain species of azaleas and rhododendrons. It is, therefore, advantageous not only to know the condition of the soil but also to understand the influence of lime on the crop to be grown. Lime is too often used as a cure-all, little attention being paid to the widely differing responses exhibited by various crops.

15:13. OVERLIMING [16]

This brings us to the question of *overliming,* that is, the addition of lime until the pH of the soil is above 7. Under such conditions many crops that ordinarily respond to lime are detrimentally affected, especially during the first season following the application. With heavy soils and when farmers can afford to apply only moderate amounts of lime, the danger is negligible. But on sandy soils, low in organic matter and therefore lightly buffered, it is easy to injure certain crops even with a relatively moderate application of lime.

The detrimental influences of excess lime have been already presented in Chapter 14. (See page 403.) Consequently, they are merely outlined here for convenience:

(1) Deficiencies of available iron, manganese, copper or zinc may be induced.

(2) Phosphate availability may decrease due to the formation of complex and insoluble calcium phosphates.

(3) The absorption of phosphorus by plants and especially its metabolic use may be interfered with.

(4) The uptake and utilization of boron may be hindered.

(5) The drastic change in pH may, in itself, be detrimental.

With so many possibilities and with such complex, biocolloidal interrelations to deal with, it is easy to see why overliming injuries in many cases have not been satisfactorily explained.

[16] See Lynd, J. Q., and L. M. Turk, "Overliming Injury on an Acid Sandy Soil," *Jour. Amer. Soc. Agron.,* 40: 205–215, 1948. See also Purvis, E. R., and O. W. Davidson, "Review of the Relation of Calcium to Availability and Absorption of Certain Trace Elements by Plants," *Soil Sci.,* 65: 111–116, 1948.

15:14. PRACTICAL PROBLEMS RESPECTING LIME

The use of lime in a practical way raises three questions. If the first is answered in the affirmative, the other two present themselves in logical sequence. The three questions are: (1) Shall lime be applied? (2) Which form shall be used? (3) What shall be the rate of application? These queries will be considered in order.

15:15. SHALL LIME BE APPLIED?

The old idea respecting lime was that of a *cure-all*—that there would be no harm in trying it; and perhaps it might be beneficial. Such an attitude should now be a thing of the past as it may lead to a waste of money and in some cases to overliming. Besides, only a few plants such as alfalfa and sweet clover, for instance, require other than moderate amounts of active calcium and magnesium and even these crops will grow vigorously on slightly acid soils. In many cases the fertility level is the critical factor. Hence, caution is necessary.

Soil pH and crops to be grown. In coming to a decision as to the desirability of applying lime, the chemical condition of the soil itself should be examined. For this a pH determination commonly is made either by means of a glass electrode and potentiometer or by the less accurate indicator-dye method (page 410). Representative subsoil as well as surface samples should be examined.[17] From such tests the physiological condition of the soil in respect to lime may be inferred.

Before a recommendation can be made, however, the lime needs in general of the crop or crops to be grown should be considered. The final decision rests upon the proper coordination of these two types of information. A grouping of crops such as that shown on page 409 (Fig. 14:5) will greatly aid in deciding whether or not to lime.

Exchangeable Ca and Mg. In deciding whether or not to apply lime to a soil it would seem more logical to test it directly for the two constituents involved. Why not determine, therefore, the amounts of exchangeable calcium and magnesium present rather than depend on pH?

The situation, however, seems to be this: The activity of the exchangeable calcium and magnesium, as well as the physiological condition of the soil, depend very largely on the percentage base saturation; the higher

[17] Care should be used in the taking of soil samples. They must be representative and before testing should be thoroughly mixed. It is well to pass the sample through a medium-to-fine screen.

the latter, the less lime need be applied. Hence, unless the cation exchange capacity of a soil is known, the milliequivalents of exchangeable calcium and magnesium cannot be interpreted in terms of percentage base saturation and thereby be used in deciding whether or not the soil needs lime.

On the other hand, the pH, since it is correlated fairly closely with percentage base saturation is, in itself, an excellent indicator of the probable activity of the lime elements and of the physiological condition of the soil. Besides it is very easily and quickly determined. Here are two reasons why this test is one of the most popular and significant determinations that is now available for soil diagnosis.

15:16. FORM OF LIME TO APPLY [18]

On the basis of the ideas already presented, it is evident that five major factors should be considered in deciding on a specific brand of lime to apply. These factors are as follows:

1. Chemical guarantees of the limes under consideration.
2. Cost per ton applied to the land.
3. Rate of reaction with soil.
4. Fineness of the limestone.
5. Miscellaneous considerations (handling, storage, bag or bulk, etc.).

Guarantee and cost relations. By a purely arithmetical calculation based on factors 1 and 2 above, the cost of equivalent amounts of lime as applied to the land can be determined. These factors will show which lime will furnish the greatest amount of neutralizing power in total for every dollar expended.

For instance, the *neutralizing power* ($CaCO_3$ equivalent) of two limes, a hydroxide and a ground limestone, are guaranteed at 135 and 95 respectively. The cost of applying a ton of each to the land (all charges, including trucking and spreading) for purposes of calculation will be considered to be \$15 in the case of the hydrate and \$8 for the carbonate. Obviously, it will require only 95/135 or 0.7 of a ton of the former to equal 1 ton of the latter. The cost of equivalent amounts of neutralizing power, based on 1 ton of limestone, will therefore be \$10.50 for the hydroxide of lime and \$8 for the limestone. Unless a rapid rate of reaction were de-

[18] It is well to remark at the outset that more than 95 per cent of the agricultural lime used in the United States is ground limestone, principally because it is cheaper than other forms. Handling and storage also are factors.

sired, the advantage in this case would definitely be with the limestone.

Rate of reaction with soil. Burned and hydrated limes react with the soil much more rapidly than do the carbonate forms. For this reason, these caustic materials may be preferred where immediate reaction with the soil is required. In time, however, this initial advantage is nullified due to the inevitable carbonation of the caustic forms of lime.

In comparing carbonate containing materials, it should be remembered that highly dolomitic limestones generally react more slowly with the soil than do those which are highly calcic. This difference is due to the comparatively slow rate of reaction of dolomite, which is supplied along with calcite in dolomitic limestones. (See Fig. 15:1.) When rapid rate of reaction is not a factor, however, dolomitic limestone is often preferred due to the fact that significant quantities of magnesium are supplied by this material. Soils treated with highly calcic limestone have been known, over a period of two or three rotations, to develop a magnesium deficiency even though the pH was maintained near 7.

The fineness of the limestone under consideration is important especially if the material is high in dolomite. If it is not sufficiently pulverized to rate as a so-called *fine* lime (see rule on page 431), allowance must be made for the lack of rapid acting material by increasing the rate of application.

Miscellaneous factors. There are several miscellaneous factors that at times may be important. The handling of the caustic limes, even when bagged, is somewhat more disagreeable than working with limestone. The necessity for storage also comes in, since sometimes it is desirable to carry lime from one season to another. The limestone has the advantage here, as it does not change in storage, if kept dry, as do the others.

The question of purchasing the lime, especially the limestone, in bags or in bulk, has become increasingly important in recent years. Spreading limestone in bulk by truck has greatly reduced the handling costs. (See Fig. 15:2.) This method, however, tends to limit the choice as to when the material may be applied, since wet or plowed fields cannot be serviced by heavy machinery. The decision as to what method to use should not be finally approved, however, until the nature of the soil and the probable response of the crops have again been revewied.[19]

[19] Farmers, especially those buying lime cooperatively, may find that the decision as to the form and brand of lime is already made for them. Nevertheless, somewhere along the line most of the factors listed above had received due consideration.

15:17. AMOUNTS OF LIME TO APPLY

In respect to the amounts of lime to apply, it is well to emphasize at the outset that all recommendations thereto are only estimates. It is impossible to decide with accuracy and certainty. Too many factors are involved, among the more important being that of buffering. It must always be remembered that we are dealing with a colloidal complex, the buffering of which we are never quite sure of.

Moreover, the objective of the lime addition is to rectify properly the very indefinite physiological condition of the soil. We are never quite certain what amounts of calcium and magnesium will accomplish this or just what pH should be temporarily established.

A situation that adds to the difficulty of deciding how much lime to apply is the practice usually of adding lime only once in a rotation. Hence, the rate of application must be stepped up sufficiently to insure enough active lime during this period. This requires good judgment and experience.

In arriving at a practical decision, a number of factors should be considered. The principle ones are as follows:

1. Soil
   - Surface
     - pH[20]
     - Texture and structure
     - Amount of organic matter
   - Subsoil: pH, texture, and structure
2. Crops to be grown
3. Length of the rotation
4. Kind of lime used and its chemical composition
5. Fineness of the limestone
6. Experience

Soil characteristics. The pH test is invaluable in making decisions as it gives some idea as to the percentage base saturation of the soil and how acute is the need for lime. The texture and organic matter also are important since they are indicative of the adsorptive capacity of the soil and the strength of buffering. Naturally the higher the buffer capacity of a soil the greater must be the amount of lime applied in order to attain a satisfactory activity of calcium and magnesium and a given change in pH.

The subsoil also should be tested for pH and examined as to texture and

[20] Other chemical tests, such as the determination of cation exchange capacity, are sometimes made and are of some practical value in deciding how much lime to apply. See Peech, M., and R. Bradfield, "Chemical Methods for Estimating Lime Needs of Soils," *Soil Sci.*, 65: 35–55, 1948. This paper carries an extended bibliography.

structure. A subsoil pH markedly above or below that of the furrow-slice may justify a reduction or an increase, as the case may be, in the acre-rate of lime application. Advice as to the cropping of any soil should not be given without a knowledge of subsoil conditions.

Other considerations. The other factors listed above have already been discussed. Besides, their importance is self-evident. As to the kinds of lime, the three forms in respect to their effects on the soil are roughly in the ratio of 1 ton of representative finely ground limestone to 0.7 of a ton of commercial hydroxide to a little over 0.5 of a ton of representative oxide. The fineness of limestone is as important as chemical composition. The experience factor has been listed to emphasize the wisdom of taking advantage of lime knowledge wherever it may be found.

Suggested amounts. In ordinary practice it is seldom economical to apply more than 2 tons of finely ground limestone to the acre of mineral soil, unless it is very acid and the promise for increased crop yield exceptionally good. The data cited in Table 15:5, while more or less suggestive, serve in a general way as guides in practical liming operations for a four- or five-year rotation with average mineral soils. It is assumed that red clover is

Table 15:5. Suggested Total Amounts of Finely Ground Limestone That Should be Applied per Acre-furrow-slice of Mineral Soil for Red Clover in Rotation [21]

Need for Lime	*Limestone, Pounds per Acre*	
	Sandy Loam	*Silt Loam*
Moderate	1500–2000	2500–3500
High	2500–3500	5000–6000

the principal legume of the rotation. The recommendations are in terms of finely ground limestone. If the lime is coarser than the minimum already quoted (see page 431), or if an oxide or hydroxide is used, due allowance should be made. If alfalfa or sweet clover are to be grown, the amounts should be increased by perhaps 500 to 1,000 pounds per acre in each case.

15:18. METHODS OF APPLYING LIME AND ITS PLACE IN THE ROTATION

As already suggested, the activity of lime is greatly encouraged by contact. Hence, the more thoroughly it is mixed with the soil, the greater will

[21] In calculating these rates, the assumption is made that the amounts suggested will be used as *initial* applications. After the pH of the soil has been raised to the desired level, smaller *maintenance* rates may be satisfactory.

be the number of active centers and the more rapid and effective will be the treatment.

Methods of application. To obtain this quick action, lime is best applied to plowed land and worked into the soil as the seedbed is prepared. It should be mixed thoroughly with the surface half of the furrow slice. Top-dressing with lime and leaving it on the surface is seldom recommended except on permanent meadows and pastures.

However, it is often much more convenient and in the long run just as effective to apply the lime on the surface and plow it under. The spreading is usually done in the fall on sod land that is to be turned later that autumn or the next spring. This practice provides a longer interval during which lime may be applied and usually results in the case of a sod in a minimum of soil packing if heavy machinery is used. It also makes possible the bulk spreading of lime, using large trucks. This is becoming increasingly popular. (See Fig. 15:2.)

The time of year at which lime is applied is immaterial, the system of farming, the type of rotation, and related considerations being the deciding factors. Winter application may even be practiced.

Equipment used. A lime distributor should be used, especially if the amount to be applied is at all large. A manure spreader can be utilized and

FIG. 15:2. *The bulk application of limestone by trucks specially equipped is becoming more and more common. Because of the weight of such machinery much limestone is applied to sod land and plowed under. In some cases this same method is used to spread commercial fertilizers. (See page 521.) (Photo courtesy George Serviss, Grange League Federation.)*

even an endgate seeder may be pressed into service. Small amounts of lime may be distributed by means of the fertilizer attachment on a grain drill. Several types of distributors are available for the bulk spreading of limestone. The evenness of distribution is as important as the amount of lime used and should by no means be neglected.

The addition of small amounts of limestone, say 300 to 500 pounds an acre, often gives remarkable results, when drilled in with the crop that is being seeded. Even though the lime is not mixed thoroughly with the soil and there is little change in the pH and the physiological condition of furrow-slice as a whole, the influence on the crop may be very favorable. Apparently the lime in this case is functioning more as a fertilizer and as a means of rectifying conditions within the crop and at its root-soil interfaces rather than as an amendment for the whole furrow-slice.

Place in rotation. A discussion of the application of lime is never complete without some consideration being given to the place in the rotation at which the liming is best done. The rule is to apply the lime with or ahead of the crop that gives the most satisfactory response. Thus, in a rotation of corn, oats, fall wheat, and two years of clover and timothy, the lime is often applied when the wheat is seeded in the fall. It can then be spread on the plowed ground and worked in as the seedbed is prepared. Its effect is thus especially favorable on the new legume seeding made in the wheat.

However, application to plowed land may result in some compaction of the soil if heavy machinery is used and certainly more power is necessary than for a soil in sod. For that reason spreading on sod land is often favored. With potatoes in the rotation, the lime usually should follow this crop, especially if scab is prevalent. In practice, the place of lime in the rotation is often determined, in part at least, by expediency, since the vital consideration is, after all, the application of lime regularly and in conjunction with a suitable rotation of some kind.

15:19. LIME AND SOIL-FERTILITY MANAGEMENT

The influence of successively liming a soil over a period of years may tend to raise or lower its fertility, according to the system of management that accompanies the applications of the lime. The use of lime alone may increase crop yields for a few years. Chemical reactions will be encouraged, soil organisms will be stimulated, and more nutrients will become available for crop use. Such stimulation, however, will soon wane and, if nothing is

returned to the land, its productivity must ultimately drop back to even a lower level than before the lime applications began.

This being the case, farm manures, crop residues, legumes, and superphosphate should be utilized to the fullest extent in connection with the lime. And when this combination is insufficient to keep up the fertility, fertilizers carrying nitrogen and potash as well as phosphates should be resorted to. Trace elements may be required in addition, especially boron. Lime improperly used exhausts the soil, but when rationally supplemented, it becomes one of the most important factors in the maintenance of the fertility and the productivity of acid soils.

CHAPTER

16

The Nitrogen Economy of Soils

OF THE various plant nutrients, nitrogen probably has been subjected to the greatest amount of study and even yet its higher plant and microbiotic relationships are receiving much attention. And there are very good reasons. The amount in the soil is small, while the quantity withdrawn annually by crops is comparatively large. At times the soil nitrogen is too readily soluble and is lost in drainage; at times it suffers volatilization; at other times it is definitely unavailable to higher plants. Moreover, its effects on plants usually are very marked and rapid. Thus, over-applications sometimes occur which may be harmful. All in all, nitrogen is a potent nutrient element that should not only be conserved, but also carefully regulated.

16:1. THE INFLUENCE OF NITROGEN ON PLANT DEVELOPMENT [1]

Favorable effects. Of the three elements usually applied in commercial fertilizers, nitrogen seems to have the quickest and most pronounced effect. It tends primarily to encourage aboveground vegetative growth and to impart to the leaves a deep green color. With cereals it increases the plumpness of the grains and their percentage of protein. With all plants nitrogen is a regulator in that it governs to a considerable degree the utilization of potassium, phosphorus, and other constituents. Moreover, its application tends to produce succulence, a quality particularly desirable in certain crops such as lettuce and radishes.

[1] Good discussions of the effects of the various nutrients on plant growth are given by Russell, E. J., *Soil Conditions and Plant Growth*, Longmans, Green and Company, New York, 1949. Also see Prianishnikov, D. N., *Nitrogen in the Life of Plants*, translation by S. A. Wilde, Kramer Business Service, Inc., Madison, Wis., 1950.

Plants receiving insufficient nitrogen are stunted in growth and possess restricted root systems. The leaves turn yellow or yellowish-green and tend to drop off. The addition of available nitrogen will cause a remarkable change, indicative of the unusual activity of this element within the plant.

Oversupply detrimental. Because of the immediate effect on plants of the application of available nitrogen compounds, one may be led to recommend higher applications than are necessary. Such a suggestion is unfortunate, since nitrogen is expensive and is easily lost from the soil. Moreover, of the three fertilizer constituents, it is the only one which, when added somewhat in excess, will result in harmful effects on certain crops. Very dark green, soft, and sappy leaves are an indication of an oversupply of nitrogen. The possible and important detrimental effects of this element may be listed as follows:

1. Nitrogen may *delay maturation* by encouraging excessive vegetative growth, which remains green beyond the normal time of ripening.
2. It may *weaken the straw* and encourage *lodging* in grain.
3. Nitrogen may *lower quality*. This is especially noticeable in certain grains and fruits, such as barley and peaches.
4. It may on occasion *decrease resistance* to *disease*.

It must not be inferred, however, that all plants are detrimentally affected by large amounts of nitrogen. Many crops such as the grasses, lettuce, radishes, and the like should have plenty of this element for their best and most normal development. With such crops, therefore, the detrimental effects cited above are not to be expected unless exceedingly large quantities of nitrogen become available. Nitrogenous fertilizers may be used freely in such cases, the cost of the materials in respect to the value of the crop increases being the major consideration.

16:2. THE NITROGEN CYCLE [2]

In all soils there is a very considerable intake and outgo of nitrogen in the course of a year, accompanied by many complex transformations. Some of these changes may be controlled more or less by man, while others are beyond his command. This interlocking succession of reactions, reversible, infinitely recurrent, and largely biochemical, constitutes what is known as the *nitrogen cycle*. (See Fig. 16:1.) It has attracted scientific study for years and its practical significance is beyond question.

The nitrogen income of arable soils is derived from such materials as

[2] For an over-all and well documented consideration of soil nitrogen, see Ensminger, L. E., and R. W. Pearson, "Soil Nitrogen," *Advances in Agronomy*, Vol. 2: 81–111, A. G. Norman, ed., 1950.

crop residues, green manures, farm manure, commercial fertilizers, and ammonium and nitrate salts brought down by precipitation. In addition, there is the fixation of atmospheric nitrogen accomplished by certain microorganisms. The outgo is due to crop removal, to drainage, to erosion, and to loss in a gaseous condition both elemental and as ammonia.

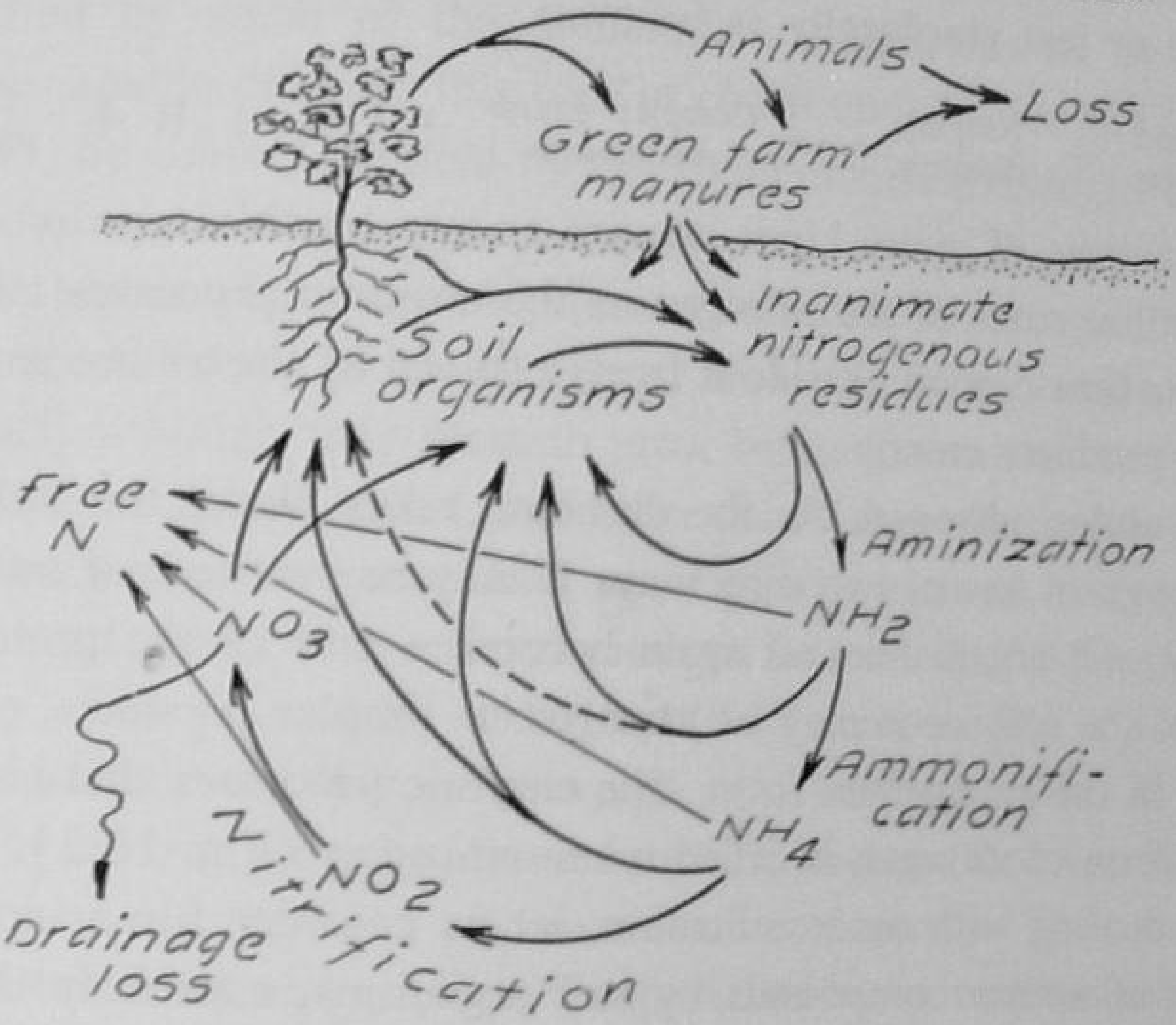


FIG. 16:1. The main portion of the nitrogen cycle. In tracing the transfers, it is well to begin with the nitrogenous organic residues. Additions due to microbial fixation of nitrogen, rain, and fertilizers are not shown.

Much of the nitrogen added to the soil undergoes many transformations before it is removed. The nitrogen in organic combination is subjected to especially complex changes. Proteins are converted into various decomposition products and finally some of the nitrogen appears in the nitrate form. Even then it is allowed no rest, as it is either appropriated by microorganisms and higher plants, or is removed in drainage, or is lost by volatilization. And so the cyclic transfer goes on and on. The mobility of nitrogen is remarkable, rivaling carbon in ease of movement and surpassing calcium in the variety and complexity of its transformations.

16:3. NITROGEN TRANSFORMATIONS IN SOILS[3]—AMINIZATION

The proteins and allied compounds, which largely constitute the nitrogenous matter commonly added to soil, are of little value directly to higher

[3] The amount of nitrogen in mineral soils and its relationship to the soil organic matter is dealt with on page 169 and ff.

plants. They can be readily used, however, by the heterogeneous soil organisms, both plant and animal. As a result of the enzymic digestion induced by these organisms, such compounds readily break down into amino compounds such as proteoses, peptones, and finally to amino acids. Hence, the process is spoken of as *aminization.* This transformation may be indicated more or less graphically as follows:

$$\begin{matrix}\text{Proteins and} \\ \text{near-proteins}\end{matrix} + \begin{matrix}\text{Enzymic} \\ \text{digestion}\end{matrix} \longrightarrow \begin{matrix}\text{Complex amino} \\ \text{compounds}\end{matrix} + CO_2 + E + \begin{matrix}\text{Other} \\ \text{products}\end{matrix}$$

Soil organisms of many kinds acquire energy by this type of digestion and also utilize some of the nitrogen as the enzymic processes take place. At the same time carbon dioxide is freely evolved as the amino compounds and other products emerge.

Fate of amino nitrogen. As the digestion takes place, the nitrogen involved may go in one of two directions. It may be synthesized into the cell contents of soil organisms and again become a part of the proteinaceous complex of the soil, or it may be changed to simpler products, eventually appearing in the ammonium form. The enzymic processes that give rise to the latter form of nitrogen is called *ammonification* (Fig. 16:1).

Before dealing with ammonification, let us consider for a moment the utilization of amino compounds by soil organisms, especially the microflora. Microorganisms, particularly those of a heterotrophic nature, when in need of nitrogen seem to use amino forms very readily. But while higher plants may possibly directly employ amino nitrogen, such an appropriation occurs so sparingly as to merit here no more than passing notice.

16:4. AMMONIFICATION

As already indicated, the same organisms, in general, that facilitate aminization also promote ammonification. In so doing, they tap ready sources of energy as well as appropriate some of the nitrogen involved. The enzymic process may be indicated as follows.[4]

$$\underset{\substack{\text{amino} \\ \text{combination}}}{R\text{-}NH_2} + HOH \xrightarrow[\text{Hydrolysis}]{\text{Enzymic}} R\text{-}OH + NH_3 + \text{Energy}$$

$$2\ NH_3 + H_2CO_3 \longrightarrow (NH_4)_2CO_3 \rightleftharpoons 2\ NH_4^+ + CO_3^{=}$$

Ammonification seems to proceed to the best advantage in well-drained aerated soils with plenty of active basic material present. It will take place

[4] R represents large organic complexes with which NH_2 is associated in amino compounds.

to some extent under almost any condition, however, due to the great number of different organisms capable of accomplishing such a change. This is one of the advantages of a general-purpose flora and fauna.

Utilization of ammonium compounds. The fate of the ammoniacal nitrogen (as shown in Fig. 16:1) is three-fold. *First,* considerable amounts are appropriated by some of the ammonifiers themselves or by other soil organisms capable of using this type of compound. Mycorrhizal fungi (see page 134), no doubt, are able to absorb ammoniacal nitrogen and pass it on in some form to their host.

Second, higher plants are able to use this form of nitrogen,[5] often very readily indeed. Young plants of almost all kinds are especially capable in this respect, although they seem to grow better if some nitrate nitrogen is also available. Azaleas, laurel, and other plants that require a low-lime soil are additional cases in point. Still other plants, such as lowland rice, for example, even prefer ammoniacal nitrogen instead of the nitrate.

Finally, when plant and animal synthesis temporarily is satisfied the remaining ammonium nitrogen may go in a third direction. It is readily oxidized by certain special-purpose forms of bacteria that use it, not only as a source of nitrogen, but also as a source of energy. Thus, one arrives at a much-talked-of and perhaps comparatively over emphasized phase of biochemistry—*nitrification.* It is so named because its end product is nitrate nitrogen.

16:5. NITRIFICATION [6]

Nitrification is a process of enzymic oxidation brought about by certain special-purpose bacteria. It seems to take place in two coordinated steps, two distinct groups of bacteria being involved. As shown below, the first step is the production of nitrous acid by one group of bacteria, apparently followed immediately by its oxidation to the nitrate form by another. (See Fig. 16:2 for this organism.) The enzymic changes are represented very simply on the next page.[7]

[5] See Allison, F. E., "Forms of Nitrogen Assimilated by Plants," *Quart. Rev. Biol.,* 6: 313–321, 1931; and "The Comparative Effects of Concentrated Nitrogenous Fertilizers on Permanent Soil Acidity," *Jour. Amer. Soc. Agron.,* 23: 878–908, 1931. See also Tiedjins, V. T., "Factors Affecting Accumulation of Ammonia and Nitrate Nitrogen, Particularly in Tomato and Apple," *Plant Physiol.,* 9: 31–57, 1934.

[6] The literature on nitrification is voluminous. For a comprehensive discussion, consult Waksman, S. A., *Principles of Soil Microbiology.* The Williams and Wilkins Company, Baltimore, 1932.

[7] The enzymic oxidations involved in nitrification are exceedingly complex. Hence, this simple method of representation may be somewhat misleading.

$$2\ NH_4^+ + 3\ O_2 \xrightarrow[\text{Oxidation}]{\text{Enzymic}} 2\ NO_2^- + 2\ H_2O + 4\ H^+ + \text{Energy}$$

$$2\ NO_2^- + O_2 \xrightarrow[\text{Oxidation}]{\text{Enzymic}} 2\ NO_3^- + \text{Energy}$$

Since the conditions favoring the two reactions are practically the same, the second transformation is thought to follow so closely on the first as to preclude any great accumulation of the nitrite. This is fortunate, as this ion in any concentration is toxic to higher plants. As a consequence, nitrification is often discussed as though the transformation was only one step.

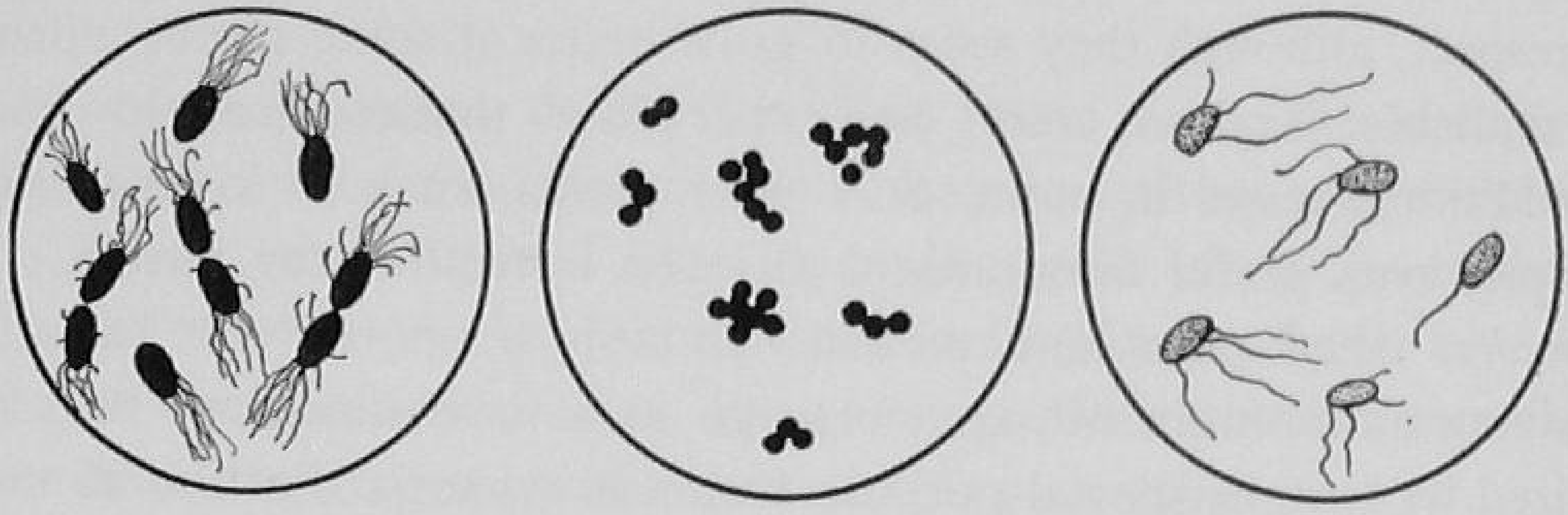


FIG. 16:2. *Some soil organisms especially important in the nitrogen cycle. Left to right,* Azotobacter, *nitrate bacteria, and nodule organisms of alfalfa.*

Organisms concerned. The organisms in this case are all special purpose and autotrophic (see page 138), in contrast to the general purpose and heterotrophic organisms concerned with aminization and ammonification. They obtain most of their energy by the oxidation of inorganic compounds. Like higher plants, they acquire carbon from carbon dioxide, at the same time respiring quantities of this gas.

Collectively, the nitrifying organisms are called nitrobacteria. Of these the *Nitrosomonas* and *Nitrosococcus* are concerned in the conversion of ammonia into nitrites. The organisms having to do with the oxidation of nitrites to nitrates are generally designated as *Nitrobacter*. In common usage

Mumford has obtained evidence that hydroxylamine and hyponitrous acid are intermediate between ammonium nitrogen and the nitrite.

$$NH_3 \longrightarrow NH_2OH \longrightarrow H_2N_2O_2 \longrightarrow HNO_2$$

Mumford, E. M., "The Mechanism ot Nitrification," *Chem. Soc. Proc.* (London), 30: 36, 1914. Also Corbet, A. S., "Formation of Hyponitrous Acid as an Intermediate Compound in the Biological or Photochemical Oxidation of Ammonia to Nitrous Acid. I. Chemical Reactions," *Biochem. Jour.* 28, No. 4: 1575–1582, 1934; and "II. Micro-Biological Oxidation," *ibid.*, 29, No. 5: 1086–1096, 1935.

these two groups of bacteria are simply spoken of as *nitrite* and *nitrate* organisms.

It is necessary to remark in this connection that other soil organisms probably are able to produce nitrate by-products. There is some evidence that nitrates are formed from ammonium compounds without a detectable appearance of the intermediate nitrites.[8] It is reasonable to suppose that simple amino compounds may be subject to the same type of over-all transfer. It is also possible that photochemical oxidation may take place in tropical soil.[9] How extensive such forms of nitrification are cannot be stated. Apparently, however, the bilateral oxidation already sketched (reaction on page 452) is the most important in a practical way.

16:6. SOIL CONDITIONS AFFECTING NITRIFICATION

The nitrifying bacteria are extremely sensitive to their environment, much more so than the heterotrophic aminizing and ammonifying organisms. As a result, nitrification is a weak link of the nitrogen cycle. Consequently, soil conditions that influence the vigor of nitrification deserve practical consideration. They are: (1) aeration, (2) temperature, (3) moisture, (4) active lime, (5) fertilizer salts, and (6) the nitrogen-carbon ratio.

Aeration.[10] Since nitrification is a process of oxidation, any procedure that increases the aeration of the soil should, up to a certain point, encourage it. Plowing and cultivation, especially if granulation is not impaired, are recognized means of promoting nitrification.[11]

Temperature. The temperature most favorable for the process of nitrification is from 80°–90° F. At a temperature of 125° F. nitrification practically ceases. At freezing or below, nitrification will not take place, but at about 40° F. it begins and slowly increases in intensity until the optimum temperature is reached. The lateness with which nitrification attains its

[8] Kaserer, H., "On Some New Nitrogen Bacteria with Autotrophic Habits of Life," (Trans.), *Ztschr. Angew. Chem.*, 19: 1681, 1906.

[9] Rao, Gopala G., "Newer Aspects of Nitrification: I," *Soil Sci.*, 38: 143–159, 1934; and Corbet, A. S., "The Formation of Hyponitrous Acid as an Intermediate Compound in the Biological and Photochemical Oxidation of Ammonia to Nitrous Acid, II. Microbiological Oxidation," *Biochem. Jour.*, 29: 1086–1096, 1935.

[10] See Amer, F. M., and W. V. Bartholomew, "Influence of Oxygen Concentration in Soil Air on Nitrification," *Soil Sci.*, 71: 215–220, 1951.

[11] Call, L. E., and M. C. Sewell, "The Relation of Weed Growth to Nitric Nitrogen Accumulation in Soils," *Jour. Amer. Soc. Agron.*, 5: 35–44, 1918.

Lyon, T. L., "Intertillage of Crops and Formation of Nitrates in Soil," *Jour. Amer. Soc. Agron.*, 14: 97–109, 1922.

full vigor in the spring is well known, nitrate of soda or ammonium nitrate sometimes being used to offset the delay.

Moisture. The rate with which nitrification proceeds in a soil is governed to a marked extent by the water content, the process being retarded by both very low and very high moisture conditions. In practice, it is safe to assume that the optimum moisture as recognized for higher plants is also optimum for nitrification. One reservation, however, must be made. Nitrification will progress appreciably at moisture contents at or even below the wilting coefficient for higher plants.

Active lime. It is a very common observation that lime stimulates nitrification in soils. Apparently, the process of oxidation requires an abundance of active bases. This accounts in part for the feeble nitrification in acid mineral soils and the seeming sensitiveness of the organisms to a low pH. As a matter of fact, however, acidity itself within reasonable limits seems to have little influence on nitrification when adequate bases are present. This is especially true of peat soils. At pH values even below 5 these soils may show remarkable accumulations of nitrates. (See page 382.)

Fertilizers. Small amounts of many kinds of salts, even those of the trace elements, stimulate nitrification. Sodium nitrate, unless applied in excessive amounts, promotes the nitrification of dried blood and cottonseed meal. Phosphates are especially effective with all types of soil organisms, as well as the nitrifiers. The same is true in respect to potash salts. In general, the stimulation of soil bacteria by the application of fertilizers is coordinate with the stimulation ordinarily observed in higher plants. Rational fertilization, therefore, promotes nitrification and other microbial activities as well as the growth of crops.

Carbon-nitrogen ratio. The significance of the carbon-nitrogen ratio has already been rather fully considered (page 164) so that the explanation here may be brief. Carbohydrates, whatever their source, readily supply energy to the general-purpose organisms of the soil, and, under favorable conditions, a tremendous multiplication of this rough-and-ready group is initiated. As a result, all of the inorganic nitrogen that is available in the soil is quickly converted to organic forms in microbial tissue. Nitrification is thus more or less at a standstill, because of a lack of ammoniacal nitrogen, this also having been swept up by the decay organisms. Thus, a competition with higher plants for nitrogen is initiated, often of a most serious nature.

After the carbonaceous matter has partially decomposed so that ener-

gizing material is no longer abundant, nitrogen assimilation slows down and by-product ammonium compounds appear in the soil. Conditions may now become favorable for nitrification, and nitrates may again accumulate in the soil. Thus, the carbon-nitrogen ratio, through its selective influence on soil microorganisms, exerts a powerful control on nitrification and the presence of nitrate nitrogen in the soil. (See Fig. 6:4, page 167.)

16:7. THE FATE OF NITRATE NITROGEN

The nitrate nitrogen of the soil may go in four directions (see Fig. 16:1). It may (1) be used by microorganisms, and (2) by higher plants, it may (3) be lost in drainage, and under certain conditions it may (4) escape from the nitrogen cycle in a volatile condition.

Use by soil organisms and plants. The assimilation of nitrate nitrogen by soil organisms and higher plants has already been dealt with, and only a few words more are necessary thereto. So voracious is the microorganic flora at times that it competes seriously with higher plants. It is probable that a large proportion of the nitrate formed during the year is appropriated by soil organisms. Higher plants thus not only feed on by-product nitrogen, but they must also be satisfied with what is left by the general-purpose soil flora and fauna. Nevertheless, field crops remove from 60 to 100 pounds of nitrogen yearly per acre.

Leaching and volatilization. The amount of nitrate nitrogen found in *drainage water,* the third avenue of loss, is not usually very great, especially if the soil carries a crop. It is evident from data already quoted (pages 247 and 249) that perhaps the average annual removal of nitrogen from a representative arable mineral soil by leaching is in the order of 5 or 6 pounds an acre. Compared to the removal by crop plants, this loss is moderate. With bare soils, however, the withdrawal by leaching is much greater.

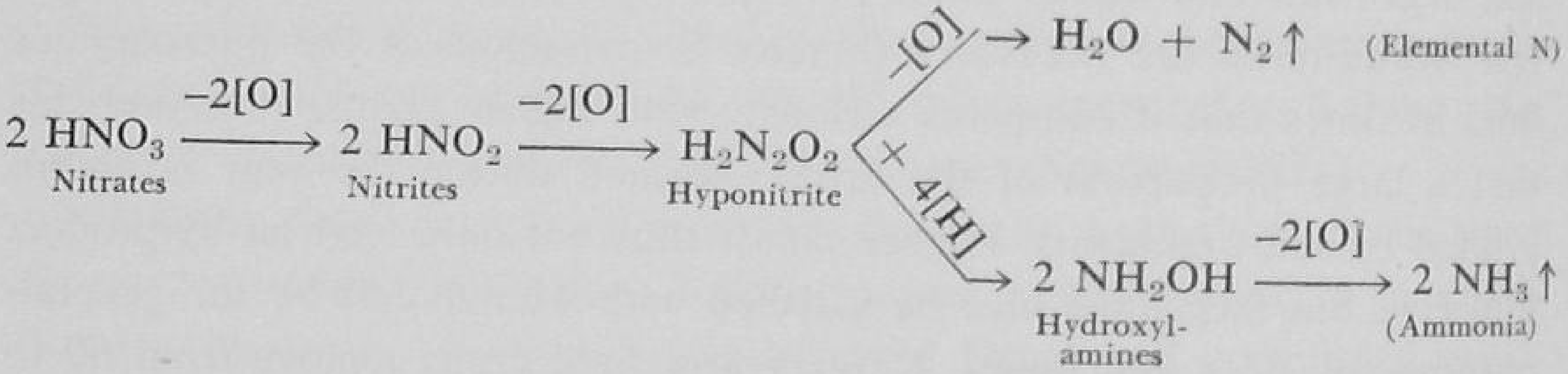
Under certain conditions, especially those of poor drainage and aeration, it seems probable that nitrate, nitrite, ammoniacal, and even simple amino compounds in the soil may be *reduced*—their nitrogen, at least in part, escaping in elemental form. The various phases of reduction will be considered in the next section.

16:8. THE VOLATILIZATION OF SOIL NITROGEN

The conditions under which the volatilization of soil nitrogen occurs are not well understood, but most authorities agree that this loss is greatly encouraged by poor drainage and lack of aeration. The maintenance of the

soil in a bare condition and the presence of excessive amounts of mobile nitrogenous compounds may also be important factors. The meagre data available in respect to such volatilization indicate that this form of loss not only is common, but also is of considerable magnitude even from well-managed cropped soils.

Reduction by organisms. The reduction of nitrate nitrogen to the elemental state has been most studied, and for a considerable time this was thought to be the principal type of volatilization. The microorganisms involved seem to be the general-purpose heterotrophic forms that under favorable conditions promote aminization and ammonification. However, under inadequate aeration [12] at least some of them seem to readily abstract oxygen from nitrates and their reduced products. The trend of the reaction may be tentatively represented as follows:



Not only can such organisms reduce nitrates and nitrites, but ammonium compounds may also be subjected to dissolution,[13] elemental nitrogen being one of the resultant products. It is possible also that simple amines and amides may be acted on in the same general way (Fig. 16:1). It is to be noted that all of these changes apparently are directly biochemical and are thought to be encouraged by poor aeration and drainage and the presence of abundant amounts of easily affected nitrogenous compounds.

Chemical reduction. There is another way [14] by which nitrogen may possibly be thrown out of the nitrogen cycle in the elemental form, conceivably in appreciable amounts. For instance, it can readily be shown that nitrites in a slightly acid solution will evolve gaseous nitrogen when brought

[12] Jones, E. J., "Loss of Elemental Nitrogen from Soils under Anaerobic Conditions," *Soil Sci.*, 70: 193–196, 1951.

[13] Kaserer, H., "On Some New Nitrogen Bacteria with Autotrophic Habits of Life," (Trans.), *Ztschr. Angew. Chem.*, 19: 1681, 1906.

[14] Wilson, J. K., "Soil Algae as Reducers of Nitrate to Nitrite," *Proc. Soil Sci. Soc. Amer.*, 6: 196, 1941; and *Nitrous Acid and the Loss of Nitrogen*, Cornell Univ. Agr. Exp. Sta., Memoir 253: 1–36, 1943. For a more conservative stand consult Allison, F. E. and J. Doetsch, "Nitrogen Gas Production by the Reaction of Nitrites with Amino Acids in Slightly Acidic Media," *Soil Sci. Soc. Amer.*, 15: 163–166, 1950.

in contact with certain ammonium salts, with simple amines, such as urea, and even with non-nitrogenous sulfur compounds and carbohydrates. The following reaction is suggestive of what may occur to urea.

$$\underset{\text{Nitrite}}{2\ HNO_2} + \underset{\text{Urea}}{CO(NH_2)_2} \longrightarrow CO_2\uparrow + 3\ H_2O + 2\ N_2\uparrow$$

It is well to note that the type of volatilization pictured above is strictly chemical and does not require adverse soil conditions. In fact, it probably occurs most readily when nitrification is vigorous and when the soil is most favorable for the growth of higher plants. Indeed such reduction may be just as normal a feature of the nitrogen cycle as are aminization, ammonification and nitrification. Its practical importance, of course, will depend upon the amount of nitrogen that thereby escapes from the soil.

Quantity of N volatilized. Since gaseous nitrogen is unavailable to higher plants, any extensive reduction, no matter what the mechanism may be, undoubtedly is a serious drain on the nitrogen cycle. In a fifteen-year lysimeter experiment at Cornell University [15] with a soil cropped ten years and kept bare five, the nitrogen loss, unaccounted for by crop removal and drainage, amounts to about 25 pounds an acre a year. Volatilization losses obtained in the same way at the New York State Experiment Station [16] with cropped lysimeter soils ranged from 11 to 80 pounds.

Unpublished results from the Cornell lysimeters covering a period of fifteen years showed a loss of nitrogen of from 40 to 45 pounds an acre, a year unaccounted for. The soil studied was a well-drained sandy loam cropped to vegetables and heavily fertilized either with nitrate of soda or sulfate of ammonia.

That such losses are not confined to humid-region soils is indicated by the work of Bracken and Greaves.[17] Soil samples from twenty-one localities in the Cache and Juab valleys of Utah were studied. Conservative calculations indicated that at least one-half of the total loss of nitrogen from cropped soils as compared to virgin land was not accounted for by leaching, erosion, and crop removal. Volatilization must have been active.

[15] Lyon, T. L., and J. A. Bizzell, "Nitrogen Economy in Dunkirk Silty Clay Loam," *Proc. and Papers, First Internat. Cong. Soil Sci.*, 3: 619–627, 1927.

[16] Collison, R. C., H. G. Beattie, and J. D. Harlan, *Lysimeter Investigations. III. Mineral and Water Relations and Final Nitrogen Balance in Legume and Non-Legume Crop Rotations for a Period of 16 Years*, Bulletin 212, N. Y. State Agr. Exp. Sta., 1933.

[17] Bracken, A. F., and J. E. Greaves, "Losses of Nitrogen and Organic Matter from Dry-land Soils," *Soil Sci.*, 51: 1–15, 1941.

Although the figures cited are by no means conclusive, it would seem that the volatilization of nitrogen from a normal arable soil may on occasion be a serious factor. The data indicate an order of loss very much greater than the removal of nitrate nitrogen in the drainage water of cultivated land. (See page 247.) The only suggestions that can be made at present for the control of volatilization is to keep a crop on the land as much as possible, provide for adequate drainage and tilth, and avoid an excess at any one time of active nitrogenous compounds in the soil.

16:9. MAJOR DIVISIONS OF THE NITROGEN CYCLE

The discussion so far has concerned itself with that part of the nitrogen cycle dealing with nitrogen already in the soil or plant. (See Fig. 16:1.) It is to be noted that two general types of enzymic activities are current therein: (1) synthetic or building-up procedures, and (2) breakdown and simplifying processes such as aminization, ammonification, nitrification, and reduction. At any one time most of the soil nitrogen is involved in the synthetic processes, a very small proportion appearing at any time in the ammoniacal, nitrite, and nitrate forms. This is fortunate, as the loss of much nitrogen by drainage and volatilization is thus avoided. Most people do not realize the importance of this situation or of the fact that higher plants are by-product feeders, living on the nitrogen left over from the metabolism of the soil fauna and flora.

The part of the nitrogen cycle, yet to be considered, concerns itself with the acquisition by the soil of nitrogen from various sources. Four ways of addition are recognized in arable soils: (1) nitrogen fixation by legume bacteria, (2) free fixation or azofication, (3) additions in rain water and snow and (4) application of nitrogen in fertilizers, farm manure, and green manures. They will be considered in order.

16:10. FIXATION OF ATMOSPHERIC NITROGEN BY NODULE BACTERIA [18]

It has long been recognized that certain crops such as the clovers, alfalfa, peas, beans, and others improve the soil in some way, making it

[18] The literature on the fixation of nitrogen by microorganisms is exceedingly copious. One may best begin with Waksman, S. A., *Soil Microbiology*, The Williams and Wilkins Company, Baltimore, 1932. Also see Norman, A. G., "Recent Advances in Soil Microbiology," *Proc. Soil Sci. Soc. Amer.*, 11: 9–15, 1946; and Clark, F. E., "Soil Microorganisms and Plant Roots," *Advances in Agronomy*, Vol. I: 242–282, A. G. Norman, ed., Academic Press, Inc., New York, 1949.

possible to grow larger yields of cereals after these plants have occupied the land. Within the last century the benefit has been traced to the fixation of nitrogen through the agency of bacteria contained in nodules on the roots of certain host plants. The specific plants so affected belong, with a few exceptions,[19] to the family of legumes.

Nodule formation. The legume organisms live in the root nodules, take free nitrogen from the soil air, and synthesize it into complex forms. The nodules evidently are the result of an irritation of the root surface, much as a gall is caused to develop on a leaf or on a branch of a tree by an insect. The entrance of the organisms normally is effected through the root hairs. The infection tube ultimately extends the entire length of the root hair and into the cortex cells of the rootlets, where the growth of the tubercle starts and where the fixation of nitrogen occurs (See Figs. 16:2 and 16:3.)

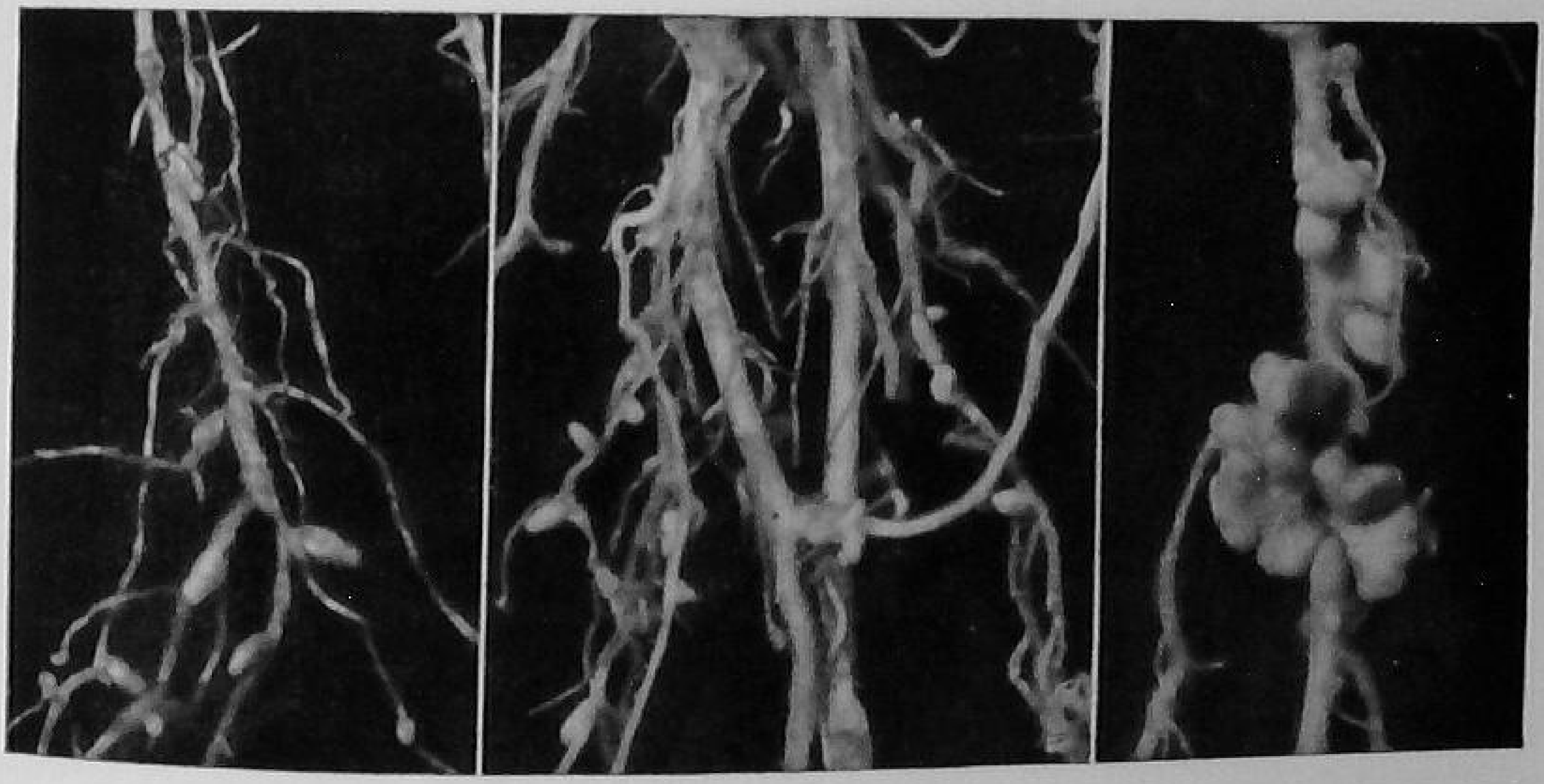


FIG. 16:3. *Nodules on the roots of legumes. Left to right, red clover, alfalfa, and field peas. Although the nitrogen fixing bacteria are segregated in the nodules, they apparently freely use the juices of the host plant as a source of energy. The nitrogen fixed may go in three directions—(1) appropriated by the host, (2) used by non-legumes growing in close association, and (3) left in the soil when the nodules slough off and decompose.*

How the plant absorbs this nitrogen after it has been secured by the bacteria is not well understood; nor is it known in exactly what form the nitrogen is at first fixed, although amino and amide forms very soon

[19] Alnus, Coriaria, Elaeagnaceae, and a few other nonlegumes carry root nodules similar to those of legumes. See Fred, E. B., I. L. Baldwin, and Elizabeth McCoy, *Root Nodule Bacteria and Leguminous Plants,* Madison, Wis., 1932

appear.[20] It seems likely that some of the nitrogen compounds produced within the bacterial cells are diffused through the cell wall and absorbed by the host plant.

Organisms involved. Since the plants are able to use some of this nitrogen fixed by the microbes, the relationship thus established is often spoken of as *symbiotic*. The organism is a *rhizobium* and there are a number of strains, depending on the host plants. They may, therefore, be classified according to the host as *Rhizobium meliloti* for those of alfalfa and sweet clover, *Rhizobium trifolii* for the clovers, *Rhizobium japonicum* for soybeans, and so on. As a group, they are often referred to as the *nodule* or *legume organisms* instead of by the more technical terms.

The organisms from one species of legumes are not necessarily well adapted to the ready production of effective nodules on other leguminous species.[21] Certain cross-inoculations are successful in practice, however. For instance, the organisms seem to be readily interchangeable within the clovers, the vetches, and the beans. Those from sweet clover and bur clover will inoculate alfalfa, while the bacteria may be transferred from vetch to field pea or from cowpea to velvet bean.[22] The part played by the plant is doubtless to furnish the carbohydrates that supply energy to the nitrogen-assimilating bacteria.

[20] This is a complex and highly controversial question. See Virtanen, A. I., "Mechanism of Symbiotic Nitrogen by Leguminous Plants," *Proc. Soil Sci. Soc. Amer.*, 4: 221–222, 1939; and Wilson, P. W., *The Biochemistry of Symbiotic Nitrogen Fixation*, University of Wisconsin Press, Madison, 1940.

[21] In some cases infection has been effected by proper culture. See Wilson, J. K., *Leguminous Plants and Their Associated Organisms*, Memoir 221, Cornell Univ. Agr. Exp. Sta., 1939.

[22] A partial listing of the groups within which cross inoculation may easily be made is given below:

Group 1. Alfalfa, bur clover, white sweet clover, yellow sweet clover, fenugreek, and yellow trefoil.
Group 2. Mammoth and red clover, alsike clover, crimson clover, hop clover, white clover, zigzag clover.
Group 3. Lespedeza, acacia, kudzu, cowpea, partridge pea, jack bean, velvet bean, lime bean, etc.
Group 4. Garden pea, sweet pea, horse bean, lentil, Canada field pea, hairy vetch, common vetch, purple vetch, etc.
Group 5. Soybean.
Group 6. Garden bean (numerous varieties), pinto bean, and scarlet runner.
Group 7. Lupine, serradella, blue lupine, yellow lupine, and white lupine.

Pieters, A. J., *Green Manuring*, John Wiley and Sons, Inc., New York, 1927, pp. 140–141.

The effect of inoculation. The influence of inoculation upon the crop yield and percentage of nitrogen in the legume is very striking. Data bearing upon the latter phase are shown in Table 16:1. Analyses are given for both the tops and roots of sweet clover and alfalfa grown on soil inoculated and not inoculated. The soil originally was not known to carry the legume organisms.

Table 16:1. Effect of Inoculation with the Legume Organisms on the Nitrogen Content of Sweet Clover and Alfalfa [23]
(Calculated as percentages based on dry matter)

Soil Treatment	*Sweet Clover*		*Alfalfa*	
	Tops	*Roots*	*Tops*	*Roots*
Inoculated	2.29	2.01	2.56	2.14
Not inoculated	1.37	0.88	1.51	0.71

16:11. AMOUNT OF NITROGEN FIXED BY NODULE BACTERIA

The amount of nitrogen fixed by the legume bacteria depends on many factors. The condition of the soil, especially as to aeration, drainage, moisture, and the amount of active calcium, are of prime importance. Many soils are in such a condition as to harbor only a meagre, nonvirulent flora of legume bacteria. Even when the above factors are favorable, a large amount of readily available nitrogen in the soil will discourage nodulation and thereby reduce fixation.[24]

Besides, there is the nature of the host plant and the age of the stand. Some legume field crops, such as alfalfa and sweet clover, facilitate a fixation of especially large amounts of nitrogen. The clovers are less effective, while some legumes can be credited with but a scanty acquisition. Lyon and Bizzell [25] in a ten-years' experiment at Ithaca, New York, report the order and relative magnitude of fixation, taking alfalfa as 100, as follows:

[23] Arny, A. C., and R. W. Thatcher, "The Effect of Different Methods of Inoculation on the Yield and Protein Content of Alfalfa and Sweet Clover," *Jour. Amer. Soc. Agron.*, 9: 127–137, 1917.

[24] Thornton, Geo. D., "Greenhouse Studies of Nitrogen Fertilization of Soybeans and Lespedeza Using Isotopic Nitrogen," *Proc. Soil Sci. Soc. Amer.*, 11: 249–251, 1946.

[25] Lyon, T. L., and J. A. Bizzell, "A Comparison of Several Legumes with Respect to Nitrogen Accretion," *Jour. Amer. Soc. Agron.*, 26: 651–656, 1934.

Alfalfa	100	Soybeans	42
Sweet Clover	67	Hairy vetch	27
Red Clover	60	Field beans	23
Alsike Clover	56	Field peas	19

Alfalfa grown continuously under the favorable conditions of the above experiment acquired symbiotically 251 pounds of nitrogen an acre yearly. A fixation ranging from 188 to 260 pounds an acre a year was recorded by Collison [26] at Geneva, New York, for the same crop.[27] Perhaps for an average crop of alfalfa, 200 to 250 pounds of nitrogen an acre would be a conservative figure for the first year and possibly for the second also. The corresponding estimate for red clover might well be 100 to 150 pounds an acre.

16:12. FATE OF THE NITROGEN FIXED BY LEGUME BACTERIA

The nitrogen fixed by the nodule organisms may go in three directions. *Firstly,* it may be appropriated by the host plant, the latter benefiting greatly by the symbiosis. *Secondly,* the nitrogen may pass into the soil itself, either by excretion or more probably by the sloughing off of the roots and especially of their nodules.[28] The crop in association with the legume may thereby benefit. This influence is a matter of common observation. The more vigorous development of timothy or bluegrass in association with clover than when grown alone is a well-known example.

Thirdly, when a legume sod is turned under, some of the nitrogen becomes available to the succeeding crop. Because of the narrow carbon-nitrogen ratio of such residues their nitrogen may swing through the nitrogen cycle with remarkable ease and may quickly appear in the ammoniacal and nitrate forms.

16:13. DO LEGUMES ALWAYS INCREASE THE SOIL NITROGEN?

With respect to the fate of the nitrogen fixed by legumes, some people assume that legumes always leave the soil on which they have been grow-

[26] Collison, R. C., H. C. Beattie, and J. D. Harlan, *Lysimeter Investigations. III. Mineral and Water Relations and Final Nitrogen Balance in Legume and Non-Legume Crop Rotations for a Period of 16 Years,* Bulletin 212, N. Y. State Agr. Exp. Sta., 1933.

[27] For further data regarding amounts of nitrogen fixed by the various legume organisms, see Fred, E. B., I. L. Baldwin, and Elizabeth McCoy, *Root Nodule Bacteria and Leguminous Plants,* Madison, Wis., 1932, p. 218.

[28] Wilson, J. K., "The Loss of Nodules from Legume Roots and Its Significance," *Jour. Amer. Soc. Agron.,* 34: 460–471, 1942.

ing definitely richer in nitrogen. As a matter of fact, the result is likely to be just the opposite, especially when the soil already is high in nitrogen or the crop is harvested and removed from the land. Beans and peas in particular are likely to leave the land depleted since they support a low nitrogen fixation. Moreover, their roots often are partially removed in harvesting.

Losses noted. Swanson [29] determined total nitrogen in the soil of a considerable number of fields in Kansas that had grown alfalfa continuously for twenty or thirty years, at the same time analyzing soil from contiguous land in native sod. In most cases, the alfalfa soil was lower in nitrogen than the sod. This tendency for legumes actually to lower instead of raise the total nitrogen has been substantiated for New York soils by carefully controlled lysimeter experiments with alfalfa and clover.[30]

Even the turning under of the entire legume crop will not always increase the nitrogen of the soil. Mooers [31] conducted experiments for ten years in which wheat, followed by cowpeas, was grown annually. On one set of plots the cowpea vines were plowed under each year, and on the other set they were removed. The surface 8 inches of soil into which the vines were plowed under lost 288 pounds of nitrogen to the acre during the experiment. However, where the vines were removed before plowing the loss was 388 pounds. It would seem that, in spite of the fixation of nitrogen that may have occurred, the influence of the wheat and other sources of loss were such as to reduce the nitrogen content of the soil.

Increase possible. However, it is possible that soils may gain some nitrogen if leguminous crops are plowed under or if a vigorous leguminous flora remains untouched for a number of years. By growing red clover on a sand very low in nitrogen and allowing the crops to remain on the ground to be plowed in every second year, Saunders and Shutt [32] at Ottawa, Canada were able to secure a gain of 52 pounds of nitrogen an

[29] Swanson, C. O., "The Effect of Prolonged Growing Alfalfa on the Nitrogen Content of the Soil," *Jour. Amer. Soc. Agron.*, 9: 305–314, 1917.

[30] Collison, R. C., H. C. Beattie, and J. D. Harlan, *Lysimeter Investigations. III. Mineral and Water Relations and Final Nitrogen Balance in Legume and Non-Legume Crop Rotations for a Period of 16 Years*, Bulletin 212, N. Y. State Agr. Exp. Sta., 1933.

[31] Mooers, C. A., *Effects of Liming and Green Manuring on Crop Yields and on Soil Supplies of Nitrogen and Humus*, Bulletin 135, Tenn. Agr. Exp. Sta., 1926.

[32] Saunders, William, and F. T. Shutt, *Clover as a Fertilizer*, Bulletin 40, Centr. Exp. Farms., Ottawa, Canada, 19–21, 1902.

acre a year during a nine-year period. Hall[33] reports an annual acre gain of 98 pounds on Broadbalk Field at the Rothamsted Experiment Station, England. This field was allowed to run wild for twenty years carrying a vegetation of legumes and nonlegumes.

These two gains, of course, include the nitrogen added in rain and by nonsymbiotic bacteria, offset by volatilization and leaching losses. The accumulation of nitrogen cited are large. However, they were obtained in soil rather low in nitrogen at the beginning of the experiments.

Legumes—nitrogen savers. It is evident, therefore, that the influence of legumes on the amount of nitrogen in the soil is uncertain. When the total soil nitrogen is high, legumes may produce a decrease, especially if the crop is removed from the land. Even when the aboveground parts are plowed under, there may still be a decrease, although some accretion is likely if the nitrogen level of the soil to begin with is low.

In general, however, the net draft of legumes on the soil nitrogen is less than that of nonlegumes, and as a consequence, their use is to be encouraged in a rotation where the maintenance of soil nitrogen is important. Legumes are usually so economical in their use of soil nitrogen that a high protein crop may often be harvested with little or no depletion of the land in respect to this element. Thus, they are nitrogen *savers.* This is a fertility axiom of the highest order.

16:14. THE EFFECT OF LEGUMES ON THE ACTIVITY OF SOIL NITROGEN

Although leguminous crops do not always bring about an increase in soil nitrogen, they usually produce a better growth of the succeeding crops than do nonlegumes. Under most circumstances, they render the organic matter of the soil more active by adding to it plant residues with a narrow carbon-nitrogen ratio. Such residues are, of course, very readily decomposed and ammonification and nitrification may soon take place. Increased yields of crops immediately following legumes are so widespread that no specific data need be quoted.

16:15. FIXATION OF ATMOSPHERIC NITROGEN BY AZOFICATION

Soils may acquire a part of their nitrogen supply independently of higher plants, fertilizers, and rainfall. There exist in soils certain micro-

[33] Hall, A. D., *Book of the Rothamsted Experiments*, E. P. Dutton and Company, Inc., New York, 1905, p. 139.

organisms, using the organic matter as a source of energy, that are able to obtain elemental nitrogen from the soil air. This nitrogen is incorporated in the bodies of these organisms and is left in the form of proteins and related compounds upon their death. The process is called *azofication*, because a major part of the fixation is ascribed to the *Azotobacter* group of bacteria. Since these organisms use the soil organic matter as a source of energy and are not directly associated with higher plants, as are the legume bacteria, the transformation is often spoken of as *nonsymbiotic* or *free fixation*.

Specific organisms involved. Although several different groups of bacteria, blue-green algae, and perhaps fungi are able to acquire atmospheric nitrogen nonsymbiotically, the major fixation in the representative soil apparently is brought about by two groups of heterotrophic bacteria. One of these is the aerobic *Azotobacter* already mentioned. (See Fig. 16:2, page 452.) The other is an anaerobic, or perhaps a facultative, bacterium called *Clostridium pastorianum*. Because of low oxygen at the soil interfaces, conditions favorable for the latter organism, are present in most soils, even when in the best of tilth. Consequently, these two groups of bacteria probably work side by side in the fixation of the nitrogen of the soil air.

It is not to be assumed that the *Azotobacter* and *Clostridium pastorianum* acquire all of their nitrogen from atmospheric sources. Since less energy is required for the acquisition of ammoniacal and nitrate nitrogen, these forms are probably readily used. In fact, in a soil high in such available nitrogen, it is doubtful whether a great deal of free fixation takes place.

Factors influencing azofication. Highly carbonaceous organic matter, since it supplies energy readily, greatly encourages azofication. Sod land, because it generally contains a large supply of organic matter with a wide carbon-nitrogen ratio, and because it is likely to be low in nitrate nitrogen, presents almost ideal conditions for azofication.

Azotobacter are notably sensitive to active calcium and, unless a fair amount of bases is present, the fixation is slow. In this respect, azofication resembles nitrification. In mineral soils the free fixation of nitrogen often begins to lag noticeably at pH 5.6 and at pH values below 5.0 becomes more or less negligible. The maintenance of the pH of mineral soils above 6.0 or even 6.5 by judicious liming is recommended. Such is not the case, however, with peat soils, since they ordinarily contain suitable amounts of active lime even at relatively high H-ion concentrations. (See page 384.)

16:16. AMOUNT OF NITROGEN FIXED BY AZOFICATION

It is difficult to determine accurately the exact amount of nitrogen fixed by azofication in soils because of the other processes involving nitrogen that are taking place simultaneously. Estimates which have been made, however, indicate that considerable quantities of nitrogen are fixed annually in this manner. For example, in an experiment conducted in England over a period of 20 years azofication was thought to account for at least 44 pounds of nitrogen per acre annually.[34] In the particular field under investigation the plants were almost entirely non-legumes and all the residues were returned to the soil.

Organic matter and azofication. Experiments conducted over a period of 10 years at Cornell University [35] showed that the cropping system used affected the rate of azofication. Certain plots were kept in grass and all crop residues were returned. The annual addition of nitrogen attributed to azofication under these conditions was about 42 pounds per acre. On comparable plots where the grass was cut and harvested each year, a minimum of 15 to 20 pounds of nitrogen per acre were fixed. Apparently the removal of the residues reduced the amount of carbonaceous material available to the nitrogen fixing organisms thereby causing a decrease in free fixation of this element.

The experiment above in which plant residues in abundance were returned to the soil is especially significant. It was under such a situation conditioned by hot, dry summers and abundant active bases that the prairie and chernozem soils acquired their high content of nitrogen and organic matter. When mature grasses with their wide carbon-nitrogen ratio become incorporated with the soil, abundant energy for the nitrogen fixing organisms is provided. And if other conditions are favorable, azofication exerts a dominant influence.

Considering the data quoted, meagre and unreliable as they are, it is perhaps fair to assume that azofication fixes in the representative arable soil at least 25 pounds of nitrogen per acre annually. Probably the real figure is nearer 40 or 50 pounds. This is of the same order of magnitude as the removal of nitrogen by volatilization. For purposes of rough cal-

[34] Hall, A. D., *Book of the Rothamsted Experiments*, E. P. Dutton and Company, Inc., New York, 1905, p. 139.

[35] Lyon, T. L., and B. D. Wilson, *Some Relations of Green-Manures to the Nitrogen of a Soil*, Memoir 115, Cornell Univ. Agr. Exp. Sta., 1928.

culation, it is perhaps not far wrong to consider that volatilization and azofication may, in general, approximately balance each other.

16:17. THE ADDITION OF NITROGEN TO SOIL IN PRECIPITATION—MAGNITUDE

Nitrogen occurring in rain and snow generally is in the nitrate and ammoniacal forms and, consequently, is readily available to plants. The amounts thus brought down are variable, usually fluctuating markedly with season and location. It is well known that the additions are greater in the tropics than in humid-temperate regions and larger in the latter than under semi-arid climates. In Table 16:2 will be found some of the more important data regarding the amounts of nitrogen thus added to the soil in various parts of the world. It will be noted that the figures are, for the most part, from temperate regions.

Apparently the ammoniacal nitrogen added to the soil in precipitation is, at least in temperate regions, always larger in amount than that in the nitrate form. It is also noticeable that, while the nitrate nitrogen is about the same for most locations, the ammonium form shows wide variations. Considering the figures as a whole, it seems safe to suggest that under a humid-temperate climate, an average of about 4½ pounds of ammoniacal and 1½ pounds of nitrate nitrogen fall on every acre of land yearly in rain and snow. Allowing for some loss in runoff, perhaps 5 pounds of nitrogen an acre actually enter the soil each year.

Table 16:2. Amounts of Nitrogen Brought Down in Precipitation

Location	*Years of Record*	*Rainfall in Inches*	*Pounds per Acre per Year*	
			Ammoniacal Nitrogen	*Nitrate Nitrogen*
Harpenden, England [36]	28	28.8	2.64	1.33
Garford, England [37]	3	26.9	6.43	1.93
Flahult, Sweden [38]	1	32.5	3.32	1.30
Groningen, Holland [39]	...	27.6	4.54	1.46
Bloemfontein and Durban, South Africa [40]	2	...	4.02	1.39
Ottawa, Canada [41]	10	23.4	4.42	2.16
Ithaca, New York [42]	11	29.5	3.65	.69

[36] Russell, E. J., and E. H. Richards, "The Amount and Composition of Rain Falling at Rothamsted," *Jour. Agr. Sci.*, 9: 309–337, 1919.

[37] Crowther, C., and A. G. Ruston, "The Nature, Distribution, and Effects upon

An annual acquisition of 5 pounds of nitrogen [43] in a readily available form to each acre of land affords some aid in the maintenance of soil fertility, as it is equivalent to about 31 pounds of commercial nitrate of soda. This addition nearly offsets the annual removal of nitrogen in drainage water from a soil under a standard rotation and more than meets such loss when the soil is in continuous sod. (See Table 9:3, page 247.) It is not unreasonable to assume, therefore, that in general it more or less completely offsets leaching losses, and from this standpoint is an important factor in the nitrogen economy of humid region soils.

16:18. PRACTICAL MANAGEMENT OF SOIL NITROGEN

The problem of nitrogen control is twofold: (1) the maintenance of an adequate supply in the soil, and (2) the regulation of the turnover in such a way as to assure a ready availability at such times as to meet crop demands. To begin with, let us draw up a rough balance sheet which will show, at least in a general way, how great the nitrogen deficit is likely to be.

Nitrogen balance sheet. It has been suggested for a representative humid-region soil that azofication approximately offsets the possible losses of nitrogen by volatilization (page 466). It has also been tentatively assumed that rain-and-snow acquisition equals in general leaching removals (see above). Therefore, the nitrogen in the harvested crops plus that carried away by erosion approximately represents the yearly deficit. Considering the former as perhaps 75 pounds an acre a year, and the latter as possibly 25

Vegetation of Atmospheric Impurities in and near an Industrial Town," *Jour. Agr. Sci.*, 4: 25–55, 1911.

[38] Von Feilitzen, H., and I. Lugner, "On the Quantity of Ammonia and Nitric Acid in Rainwater Collected near Flahult, in Sweden," *Jour. Agr. Sci.*, 3: 311–313, 1910.

[39] Hudig, J., "The Amounts of Nitrogen as Ammonia and Nitric Acid in the Rainwater Collected at Uithuizer-Meeden, Groningen," *Jour. Agr. Sci.*, 4: 260–269, 1912.

[40] Juritz, C. F., "Chemical Composition of Rain in the Union of South Africa," *S. Africa Jour. Sci.*, 10: 170–193, 1914.

[41] Shutt, F. T., and R. Dorrance, "The Nitrogen Compounds of Rain and Snow," *Proc. and Trans. Roy. Soc. Canada*, 11: 63–71, 1917.

[42] Wilson, B. D., "Nitrogen and Sulfur in Rainwater in New York," *Jour. Amer. Soc. Agron.*, 18: 1108–1112, 1926. Later data (unpub.) from Cornell substantiate Wilson's findings.

[43] The *total* nitrogen brought down by rain and snow over an acre of land may be somewhat more than the 5 pounds indicated. Dust carried down by the precipitation and blown into the rain gauges during non-rainy periods may contain some non-soluble organic nitrogen. Of course, this cannot be considered as a *net* addition since the dust came from the soil originally. See Matheson, D. H. "Inorganic Nitrogen in Precipitation and Atmospheric Sediments," *Canadian Jour. of Tech.*, 29: 406–412, 1951.

pounds for lands having a moderate slope (see Table 9:8, page 267), it seems that in a general way 100 pounds, more or less, of nitrogen an acre will be required annually to effect a balance. Such figures should be used guardedly, as they are more or less hypothetical and are designed merely to give a general concept of the problem.

Meeting the deficit. In practice, nitrogen deficits are met in four ways—crop residues, farm manure, legumes, and commercial fertilizers. The discussion of their utilization is reserved for a later and more opportune occasion. Suffice to say at this point that, although the nitrogen deficit can be met and is being met on some of the better managed farms, the average arable soil in the United States is at the present time probably suffering a slow decline in total nitrogen.[43] That crops do not show a corresponding decrease in yield (see Fig. 20:5, page 566) may be ascribed to better methods of soil management, to improved crop varieties, and to a greater activity of the nitrogen still present in the soil.

Turnover regulation. By all odds, the more difficult of the two general problems of nitrogen control is the regulation of this element after it enters the soil. Availability at the proper time and in suitable amounts, with a minimum of loss, is the ideal. The influence of climate, erosion, drainage, tillage, fertilizers, lime, and C:N ratio must be balanced against the nature and condition of the soil, the crops grown, and their particular influence on the land.

Since soils under any given climate tend to assume what may be called a *normal* or *equilibrium content* of nitrogen under ordinary methods of cropping and manuring, any attempt to raise the nitrogen content to a point materially higher than this normal will be attended by an unnecessary waste due to drainage and other losses. It would appear to be good practice, therefore, to maintain only a moderate nitrogen level in a soil. At the same time, the nitrogen should be kept suitably active by the use of legumes and other organic materials with a narrow C:N ratio, and by the applications of lime and commercial fertilizers.

This is essentially the recommendation already made for soil organic matter (page 180), and it is known to be both economical and effective. In short, the practical problem is to supply adequate nitrogen to the soil, to keep it mobile, and at the same time to protect it from excessive losses due to leaching, volatilization, and erosion.

[43] Lipman, J. G., *Preliminary Note on the Inventory and Balance Sheet of Plant Nutrients in the United States,* Bulletin 607, N. J. Agr. Exp. Sta., 1936.

CHAPTER

17 The Supply and Availability of Phosphorus and Potassium [1]

CONSIDERABLE NITROGEN can be added to soils through biochemical fixation brought about by microorganisms. If the proper legume is chosen, for example, the organisms will often fix this element from the air in quantities sufficient to temporarily increase the nitrogen already present. With other nutrient elements such as phosphorus and potassium, however, we have no such microbial aid. Consequently, other sources must be depended upon to meet the demands of plants.

There are at least four main sources of phosphorus and potassium from which we can draw in meeting these demands: (a) commercial fertilizer, (b) barnyard manures, (c) plant residues, including green manures, and (d) native compounds of these elements, both organic and inorganic, already present in the soil. Since the first three sources are to be considered in later chapters, our attention at present will be focused on the ways and means of utilizing the body of the soil as source of these mineral elements. We will begin with phosphorus.

17:1. IMPORTANCE OF PHOSPHORUS

With the possible exception of nitrogen, no other element has been as critical in the growth of plants in the field as has phosphorus. A lack of

[1] The reader who is interested in only the practical aspects of soil science may not find it necessary to consider the more detailed phases which are presented in this chapter. Principles governing the practical utilization of potassium and particularly phosphorus have been presented in previous chapters (14 and 15). Consequently, some may find it worth while to delay or even omit the reading of this chapter and to continue with the practical means of supplying nutrient elements, which are considered in Chapters 18, 19, and 20.

this element is doubly serious, since it may also result in a decrease in the ease with which other nutrients are acquired by plants. For example, prior to the extensive usage of commercial fertilizers most of our soil nitrogen was indirectly dependent upon the supply of phosphorus. This was due to the vital influence of the latter element on legume growth. Today the demand for phosphorus by nitrogen yielding legumes is still universally recognized.

The need of plants for phosphorus has been especially considered in the formulation of commercial fertilizers. This element, in the form of superphosphate, was the first to be supplied as a manufactured product. Until fairly recently the amount of "phosphoric acid" in mixed fertilizers almost invariably exceeded that of nitrogen or potash. Even today the total tonnage of phosphorus, expressed as P_2O_5, exceeds that of any other fertilizer element sold in this country.

17:2. INFLUENCE OF PHOSPHORUS ON PLANTS

It is difficult to state in detail the functions of phosphorus in the economy of even the simplest plants. Neither cell division nor the formation of fat and albumen take place adequately without it. Starch may be produced when it is lacking, but does not readily change to sugar. As seeds do not form without its presence, it undoubtedly is concerned in the production of nucleoproteids. Its close relationship to cell division may account for its presence in grains and other seeds in comparatively large amounts. Flowering and fruiting depend absolutely upon it.

Phosphorus especially hastens the maturation of the crop and in this respect it counteracts the effect of excessive nitrogen. This influence is particularly important in wet years and in cold climates where the season is short. Phosphorus also encourages root development, particularly of the lateral and fibrous rootlets. This renders it invaluable in soils that do not encourage root extension and to crops that naturally have a restricted root development. Phosphorus is especially serviceable in the production of nursery stock, which should have a strong fibrous root system. It is also notably valuable for fall-sown crops such as wheat and alfalfa. A sturdy root growth is developed which tends to counteract winter injury and prepares the plant for a rapid spring development.

The ratio of grain to straw, as well as the total yield, is increased in cereals by phosphorus. This element also strengthens the straw, thus decreasing the tendency to lodge, which is likely to occur if too much avail-

able nitrogen is present. A lack of phosphorus results in a bronzing or purpling of the leaves. Plants receiving insufficient phosphorus seem to find it difficult to obtain adequate potassium. No doubt there is a somewhat similar relationship in respect to other nutrients.

Phosphorus decidedly improves the quality of certain crops. This has been recognized in the handling of pastures in many parts of the world, a better bone development of the grazing animals resulting. The effect on the palatability of vegetables is an influence of practical concern. Phosphorus is also known to increase the resistance of some plants to disease, due possibly to a more normal cell development and to a more vigorous metabolism. Moreover, this element tends at times to alleviate the detrimental effects of overliming, perhaps by restoring the phosphate nutrition that seems to be upset by the absorption of too much calcium. (See page 404.)

17:3. THE PHOSPHORUS PROBLEM

Although the amount of total phosphorus in an average mineral soil compares favorably with that of nitrogen, it is much lower than potassium, calcium, or magnesium. (See Table 2:2, page 26.) Of even greater importance, however, is the fact that most of the phosphorus present in soils is currently unavailable to plants. Also when soluble sources of this element are supplied to soils in the form of fertilizers, their phosphorus is often "fixed" or rendered unavailable even under the most ideal field conditions. (See page 481.)

Fertilizer practices in many areas exemplify very well the problem of phosphorus availability. As already emphasized, the tonnage of phosphorus supplying materials used as fertilizers definitely exceeds that of nitrogen or potassium carriers. The removal of phosphorus from soils by crops, however, is low compared to that of nitrogen and potassium, often being only ⅓ or ¼ that of the latter elements. The necessity for high fertilizer dosage when relatively small quantities of phosphorus are being removed from soils indicates that much of the added phosphates become unavailable to growing plants.

The influence of this situation on fertilizer practice is clearly shown by the map of Figure 17:1. In 22 states more phosphorus was applied in fertilizer in 1943 than was removed in harvested crops. The map also reveals that phosphorus additions exceeded crop removal by at least 300 per cent

in 12 of the states. Since this element is lost only sparingly by leaching, the inefficiency of utilization of phosphate fertilizers is obvious.

Briefly then, the over-all phosphorus problem is threefold: (a) a small total amount present in soils, (b) the unavailability of such native phosphorus, and (c) a marked "fixation" of added soluble phosphates. Since crop removal of phosphorus is relatively low and world phosphate supplies are huge, problem (a), that of supplying sufficient total phosphorus, is not serious. Increasing the availability of native soil phosphorus and the retardation of fixation or reversion of added phosphates are, therefore, the problems of greatest importance. These two phases will be discussed following a brief review of the phosphorus compounds present in soils.

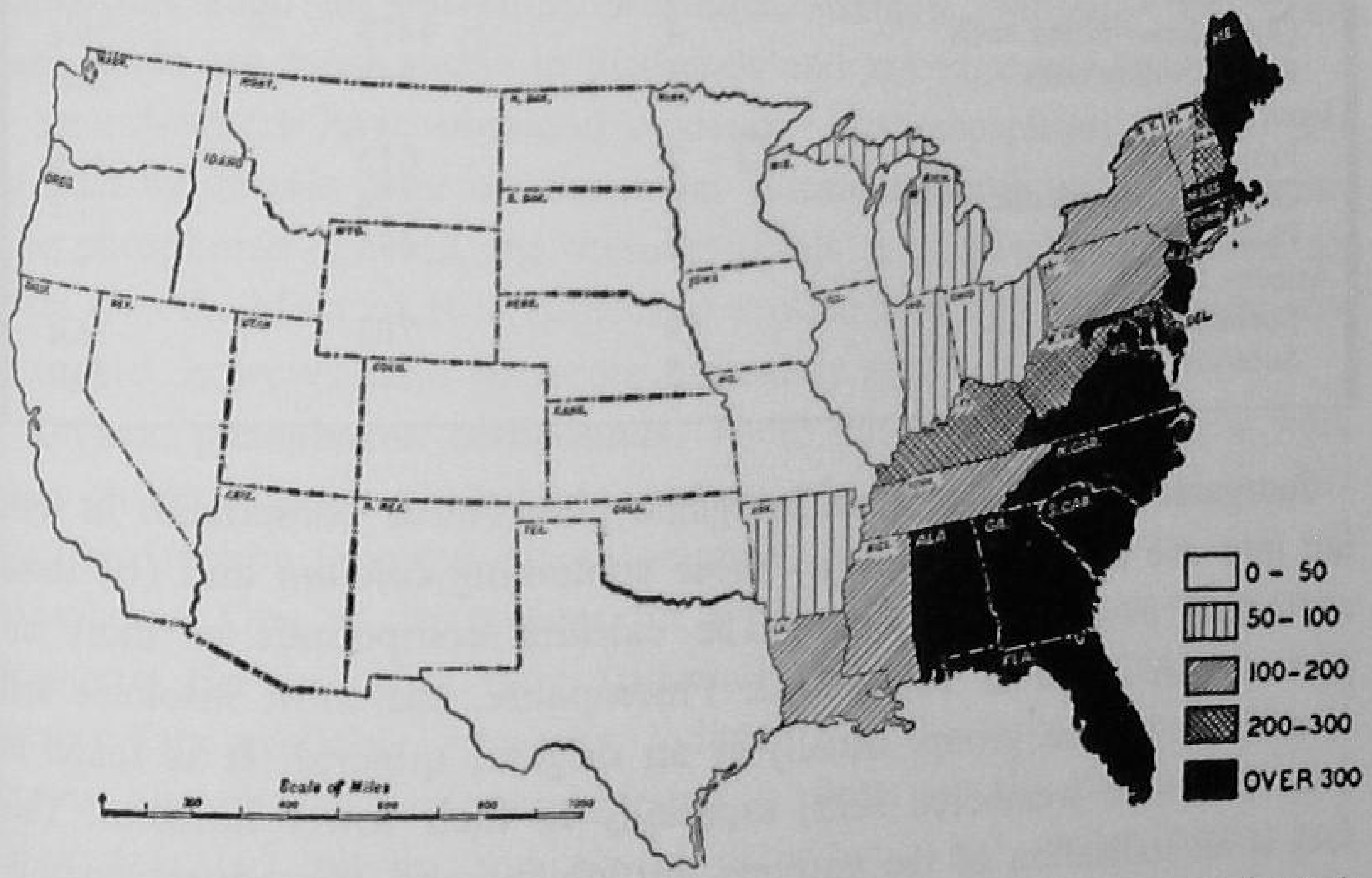


FIG. 17:1. *Phosphorus applied in fertilizers as percentage of that removed in crops harvested in 1943. Obviously the store of phosphorus in some soils is rapidly being built up. (From Cummings, R. W., "Agronomic Problems in the Agricultural Reconversion of the South,"* Proc. Soil Sci. Soc. Amer., *10:9–15, 1945.)*

17:4. PHOSPHORUS COMPOUNDS IN SOILS [2]

Both inorganic and organic forms of phosphorus occur in soils and both are important to plants as sources of this element. There is a serious

[2] For a review of compounds of phosphorus, especially the organic fraction, see Pierre, W. H., "The Phosphorus Cycle and Soil Fertility," *Jour. Amer. Soc. Agron.*, 40: 1–14, 1948 and Bremner, J. M. "A Review of Recent work on Soil Organic Matter," Part I, *Jour. of Soil Science*, 2: 67–82, 1951.

lack of information, however, on the relative amounts of these two forms in different soils. Data available from Oregon, Iowa, and Arizona (Table 17:1) give some idea of their relative proportions. Despite the variation which occurs, it is evident that a consideration of soil phosphorus would not be complete unless some attention were given to both forms.

Table 17:1. The Total Phosphorus Content in Parts per Million of Soils from Three States and the Percentage of the Total Phosphorus in the Organic Form

Soils	*No. of Samples*	*Total P ppm*	*Organic Fraction %*
Western Oregon Soils [3]			
Hill soils	4	357	65.9
Old valley—filling soils	4	1479	29.4
Recent valley soils	3	848	25.6
Iowa Soils [4]			
Prairie soils	2	613	41.6
Gray-brown podzolic soils	2	574	37.3
Planosols	2	495	52.7
Arizona Soils [4]			
Surface soils	19	703	36.0
Subsoils	5	125	34.0

Inorganic compounds. Most inorganic phosphorus compounds in soils fall into one of two groups: (a) those containing *calcium* and (b) those containing *iron* and *aluminum*. The calcium compounds of most importance are listed in Table 17:2. Fluorapatite, the most insoluble and unavailable of the group, usually is an original mineral. It is found in even the more weathered soils, especially in their lower horizons. This fact is an indication of the extreme insolubility and consequent unavailability of the phosphorus contained therein. The simpler compounds of calcium such as mono- and di-calcium phosphate are readily available for plant growth. Except on recently fertilized soils, however, these compounds are present in extremely small quantities only, since they easily revert to the more insoluble forms.

[3] From Bertramson, B. R., and R. E. Stephenson, "Comparative Efficiency of Organic Phosphorus and of Superphosphate in the Nutrition of Plants," *Soil Sci.*, 53: 215–226, 1942.

[4] Iowa data from Pearson, R. W., and R. W. Simonson, "Organic Phosphorus in Seven Iowa Profiles: Distribution and Amounts as Compared to Organic Carbon and Nitrogen," *Proc. Soil Sci. Soc. Amer.*, 4: 162–167, 1939. Arizona data from Fuller, W. H., and W. T. McGeorge, "Phosphates in Calcareous Arizona Soils, II Organic Phosphorus Content," *Soil Sci.*, 71: 45–50, 1951.

Table 17:2. **Inorganic Calcium Compounds of Phosphorus Often Found in Soils**

Compound	*Formula*	
Fluor-apatite	3 $Ca_3(PO_4)_2 \cdot CaF_2$	Solubility increases ↓
Carbonate-apatite	3 $Ca_3(PO_4)_2 \cdot CaCO_3$	
Hydroxy-apatite	3 $Ca_3(PO_4)_2 \cdot Ca(OH)_2$	
Oxy-apatite	3 $Ca_3(PO_4)_2 \cdot CaO$	
Tricalcium phosphate	$Ca_3(PO_4)_2$	
Dicalcium phosphate	$CaHPO_4$	
Monocalcium phosphate	$Ca(H_2PO_4)_2$	

Much less is known of the exact constitution of the iron and aluminum phosphates contained in soils. The compounds involved are probably basic phosphates such as dufrenite, wavellite, strengite, variscite,[5] etc. These compounds are most stable in acid soils and are extremely insoluble.

Some workers have obtained evidence[6] that phosphates are also held or fixed by certain iron or aluminum silicate minerals such as kaolinite. The phosphorus carried by these minerals is relatively unavailable for plant growth. Most of it is subject to replacement by OH-ions when lime is applied, however, and therefore ultimately may be of value.

Organic phosphorus compounds. There has been relatively less work done on the organic phosphorus compounds in soils, in spite of the fact that this fraction in some cases comprises more than half of the total soil phosphorus. One of the reasons for a lack of information on these compounds is the fact that they apparently are exceedingly complex. The meager data available, however, indicate that the three main groups of organic phosphorus compounds found in plants are also present in soils.[7] These are: (a) phytin and phytin derivatives, (b) nucleic acids, and

[5] Cole, C. V., and M. L. Jackson, "Colloidal Dihydroxydihydrogen Phosphates of Aluminum and Iron with Crystalline Character Established by Electron and X-ray Diffraction," *Jour. Phys. and Coll. Chem.*, 54: 128–142, 1950.

[6] For example, see Stout, P. R., "Alterations in the Crystal Structure of Clay Minerals as a Result of Phosphate Fixation," *Proc. Soil Sci. Soc. Amer.*, 4: 177–182, 1939; and Perkins, A. T., "Phosphate Fixation by Soil Minerals, IV. General," *Trans. Kansas Academy of Science*, Vol. 48, No. 2, 1945.

[7] See Pierre, W. H., "The Phosphorus Cycle and Soil Fertility," *Jour. Amer. Soc. Agron.*, 40: 1–14, 1948.

Bower, C. A., "Separation and Identification of Phytin and Its Derivatives from Soils," *Soil Sci.*, 59: 277–285, 1945.

Phytin is a calcium-magnesium salt of inositol phosphoric acid and is rather widely distributed in plants, especially in the seeds. Nucleic acids are found in both plants and animals and are even more complex than is phytin. They are apparently polymeric combinations of phosphoric acid, carbohydrates, and bases such as pyrimidine and purine.

(c) phospholipids. Apparently the first two of these make up most of the organic soil phosphorus, with approximately half coming from each group. In spite of the complexity of these compounds, however, certain facts concerning their properties are of considerable help in explaining phosphate availability to plants.

17:5. FACTORS THAT CONTROL THE AVAILABILITY OF INORGANIC SOIL PHOSPHORUS [8]

The availability of inorganic phosphorus is largely determined by the following factors: (a) soil pH, (b) soluble iron, aluminum and manganese, (c) presence of iron, aluminum and manganese containing minerals, (d) available calcium, (e) amount and decomposition of organic matter and (f) activities of microorganisms. The first four of these factors are interrelated since their effects are largely dependent upon soil acidity.

17:6. pH AND PHOSPHATE IONS

It will be remembered from Chapter 14 (page 404) that the availability of phosphorus to plants is determined to no small degree by the ionic form of this element. The ionic form in turn is determined by the pH of the solution in which the ion is found. Thus, in highly acid solutions only the H_2PO_4-ions are present. If the pH is increased, first the HPO_4-ions and finally PO_4-ions dominate. This situation is shown by means of the following equations:

$$\underset{\text{(Very Acid Solutions)}}{H_2PO_4^-} \overset{+OH^-}{\rightleftharpoons} H_2O + HPO^{=}_4 \overset{+OH^-}{\rightleftharpoons} H_2O + \underset{\text{(Alkaline Solutions)}}{PO^{\equiv}_4}$$

It should be remembered that at intermediate pH levels two of the phosphate ions may be present simultaneously. Thus, in solutions at pH 6.0 both H_2PO_4- and HPO_4-ions are found.

In general, the H_2PO_4- and HPO_4-ions are considered somewhat more available to plants than is the PO_4-ion. In soils, however, this relationship is complicated by the presence or absence of other compounds or ions. For example, the presence of soluble iron and aluminum under very acid conditions, or calcium at high pH values, will markedly affect the availability of the phosphorus. One can readily see, therefore, that the effect

[8] The subject of phosphorus availability has been reviewed by Dean, L. A., "Fixation of Soil Phosphorus," *Advances in Agronomy*, I: 391–411, A. G. Norman, ed., Academic Press Inc., New York, 1949. Also see Weld, A. "The Retention of Phosphate by Soil. A Review," *Jour. of Soil Sci.*, 1: 221–238, 1950.

of soil pH on phosphorous availability is determined in no small degree by the various cations present. We will first discuss the effect of these ions in acid soils.

17:7. INORGANIC PHOSPHORUS AVAILABILITY IN ACID SOILS (SEE FIG. 17:2)

Let us assume that we are working with either a nutrient solution or an organic soil very low in inorganic matter. Assume also that these media are acid in reaction but that they are low in iron, aluminum and manganese. The H_2PO_4-ions, which would dominate under these conditions would be readily available for plant growth. Normal phosphate absorption by plants would be expected so long as the pH was not too low.

Precipitation by Fe, Al and Mn ions. If the same degree of acidity should exist in a normal mineral soil, however, quite different results would be expected. Some soluble iron, aluminum, and manganese are usually found in strongly acid mineral soils. Reaction with the H_2PO_4-ions would immediately occur, rendering the phosphorus insoluble and also unavailable for plant growth.

The chemical reactions occurring between the soluble iron and aluminum and the H_2PO_4-ions probably result in the formation of so-called hydroxy-phosphates. This may be represented as follows, using the aluminum cation as an example:[9]

$$Al^{+++} + \underset{\text{Soluble}}{H_2PO_4^-} + 2\ H_2O \longrightarrow 2\ H^+ + \underset{\text{Insoluble}}{Al(OH)_2H_2PO_4}$$

In most strongly acid soils the concentration of the Fe and Al ions greatly exceeds that of the H_2PO_4-ions. Consequently, the above reaction moves to completion forming the insoluble phosphate. This leaves only minute quantities of the H_2PO_4-ion immediately available for plants under these conditions.

Fixation by hydrous oxides. It should be emphasized that the H_2PO_4-ion reacts not only with the soluble iron, aluminum, and manganese but also with insoluble hydrous oxides of these elements such as limonite and goethite. In fact, the actual quantity of phosphorus fixed by these minerals in acid soils quite likely exceeds that due to chemical precipitation by the soluble Fe, Al, and Mn cations. (See Fig. 17:2.)

[9] See Cole, C. V., and M. L. Jackson, "Solubility Equilibrium Constant of Dihydroxy Aluminum Dihydrogen Phosphate Relating to a Mechanism of Phosphate Fixation in Soils," *Proc. Soil Sci. Soc. Amer.*, 15: 84–89, 1950.

The nature of the compounds which are formed as a result of fixation by iron and aluminum oxides has not been definitely established. In recent investigations,[10] however, evidence has been obtained indicating that the

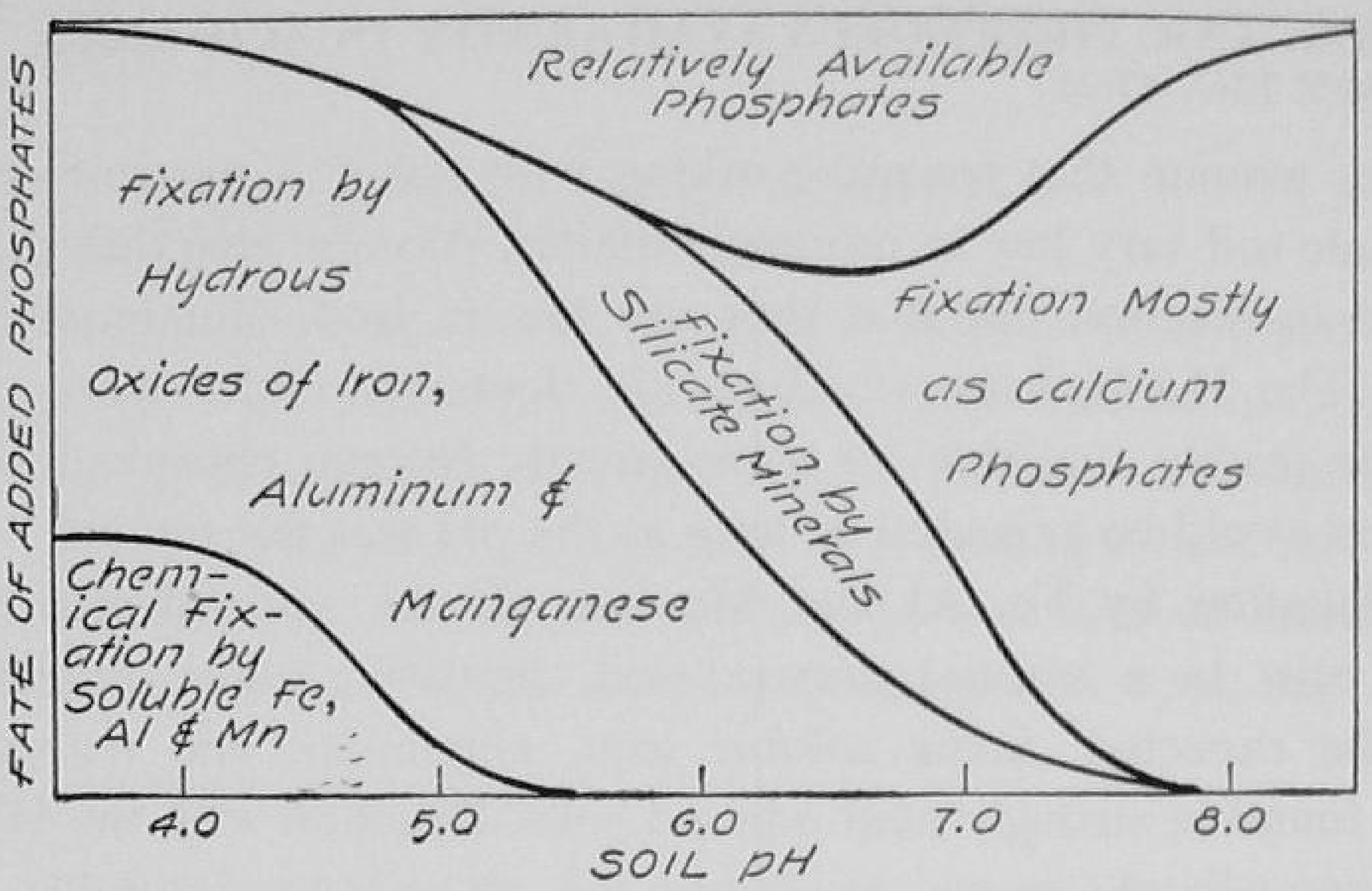


FIG. 17:2. *Diagram showing the inorganic fixation of added phosphates at various soil pH values. Average conditions are postulated and it is not to be inferred that any particular soil would have exactly the above distribution. The actual proportion remaining in an available form will depend upon contact with the soil, time for reaction, and other factors. It should be kept in mind that some of the added phosphorus may be changed to an organic form in which it would be temporarily unavailable.*

compounds resulting may be hydroxy-phosphates just as in the case of chemical precipitation described above. Their formation can be illustrated by means of the following equation, if we represent the hydrous oxide of aluminum as aluminum hydroxide:

$$\mathrm{Al}\begin{cases}\mathrm{OH}\\ \mathrm{OH}\\ \mathrm{OH}\end{cases} + \underset{\text{Soluble}}{H_2PO_4^-} \rightleftharpoons \underset{\text{Insoluble}}{\mathrm{Al}\begin{cases}\mathrm{OH}\\ \mathrm{OH}\\ H_2PO_4\end{cases}} + OH^-$$

By means of this and similar reactions the formation of several basic-phosphate minerals, containing either iron or aluminum or both, is thought to occur. Since several such compounds are possible, fixation of

[10] Swenson, R. M., V. C. Cole, and D. H. Sieling, "Fixation of Phosphate by Iron and Aluminum and Replacement by Organic and Inorganic Ions," *Soil Sci.*, 67: 3–22, 1949.

Cole, C. V., and M. L. Jackson, "Colloidal Dihydroxy Dihydrogen Phosphates of Aluminum and Iron with Crystalline Character Established by Electron and X-ray Diffraction," *Jour. Phys. and Coll. Chem.*, 54: 128–142, 1950.

phosphorus by this mechanism probably takes place over a relatively wide pH range. Also the large quantities of hydrous iron and aluminum oxides present in most soils makes possible the fixation of tremendous amounts of phosphorus in total by this means.

Thus, as both of the above equations show, the acid condition which would make possible the presence of the readily available H_2PO_4-ion in mineral soils at the same time results in conditions conducive to the vigorous *fixation* or precipitation of the phosphorus by iron, aluminum, and manganese compounds. (See Fig. 17:2.)

Fixation by silicate clays—anion exchange. A third means of fixation of phosphorus under moderately acid conditions involves silicate minerals such as kaolinite, montmorillonite, and illite. Although there is some doubt as to the actual mechanisms involved,[11] the over-all effect is essentially the same as when phosphorus is fixed by simpler iron and aluminum compounds. In many cases there apparently is a replacement of OH-ions by H_2PO_4-ions, *fixing* the phosphorus and making it unavailable for plant growth. Therefore, a general equation to represent the fixation of phosphorus by many minerals under acid conditions may be written as follows, if we consider all of the fixing agents as having a replaceable OH group.

$$\boxed{\text{mineral}}\ OH + \underset{\text{Soluble}}{H_2PO_4^-} \rightleftharpoons \boxed{\text{mineral}}\ \underset{\text{Fixed}}{H_2PO_4} + OH^-$$

As indicated by the double arrows, the above reaction is a reversible one. In other words, by adding OH-ions the equilibrium will shift to the left and H_2PO_4-ions will be released. Such a reaction represents a process known as *anion exchange* since one anion is being exchanged for another.

[11] Some workers visualize the fixation of phosphates by silicate minerals as a surface reaction between exposed OH-groups on the mineral crystal and the H_2PO_4-ions.

See Stout, P. R., "Alterations in the Crystal Structure of Clay Minerals as a Result of Phosphate Fixation," *Proc. Soil Sci. Soc. Amer.*, 4: 177–182, 1939; and Dean, L. A., and E. J. Rubins, "Anion Exchange in Soils: I Exchangeable Phosphorus and the Anion-Exchange Capacity," *Soil Sci.*, 63: 377–387, 1947.

Other investigators have evidence that the fixation of kaolinite involves an actual breakdown of the silicate mineral. This results in the formation of a basic aluminum phosphate having the same characteristic as that formed when simple aluminum compounds are phosphated.

See Low, P. F., and C. A. Black, "Phosphate-induced Decomposition of Kaolinite," *Proc. Soil Sci. Soc. Amer.*, 12: 180–184, 1947; and Swenson, R. M., V. C. Cole, and D. H. Sieling, "Fixation of Phosphate by Iron and Aluminum and Replacement by Organic and Inorganic Ions," *Soil Sci.*, 67: 3–22, 1949.

This phenomenon is probably as common in phosphate fixation as is its counterpart, cation exchange.[12]

Undoubtedly the process has considerable practical significance in that liming, which furnishes OH-ions, tends to bring about the release of some fixed phosphorus. Also, as was previously pointed out, liming reduces to a marked degree the fixation of the phosphates as iron and aluminum compounds.

17:8. INORGANIC PHOSPHORUS AVAILABILITY AT HIGH pH VALUES (SEE FIG. 17:2)

As has been emphasized elsewhere (page 404), sufficient lime can be applied to cause phosphate precipitation, this time as insoluble calcium and magnesium compounds. In alkaline solutions it will be remembered that the dominant phosphate carrier is the PO_4-ion. In the presence of magnesium and especially calcium this ion is readily precipitated,[13] and becomes quite unavailable to plants. The reversion of available phosphates, such as those found in superphosphate, to the insoluble form in alkaline soils may be represented as follows:

$$Ca(H_2PO_4)_2 + 2\ CaCO_3 \longrightarrow Ca_3(PO_4)_2 + 2\ CO_2 + 2\ H_2O$$

Although the $Ca_3(PO_4)_2$ thus formed is quite insoluble, it may be converted in the soil to even more insoluble compounds. The hydroxy-, oxy-, carbonate- or even fluor-apatite compounds, may be formed if conditions are favorable and if sufficient time is allowed. (See Table 17:2.)

This type of reversion may occur in soils of the eastern United States which have been heavily limed. It is much more serious, however, in western soils due to the widespread presence of excess $CaCO_3$. The problem of utilizing phosphates in alkaline soils of the arid West is thus fully as serious as it is on highly acid soils in the East.

[12] It is not to be inferred that anion exchange is strictly analogous to cation exchange. Adsorbed cations are released relatively easily to plants or to the soil solution. Adsorbed phosphorus, however, is very tightly held and is only sparingly available to plants.

[13] Although the absorption of the PO_4-ion by plants is not as rapid as is that of H_2PO_4- or HPO_4-ions, it is probably not sufficiently slow to seriously retard plant growth. Consequently, the unavailability of phosphorus in mineral soils between pH 7.0 and 8.0 apparently is due to precipitation as calcium and magnesium salts rather than to the inability of plants to absorb the PO_4-ion. See Pratt, P. F., and D. W. Thorne, "Solubility and Physiological Availability of Phosphate in Sodium and Calcium Systems," *Proc. Soil Sci. Soc. Amer.*, 13: 213–217, 1947.

17:9. MAXIMUM INORGANIC PHOSPHORUS AVAILABILITY

With insolubility of phosphorus occurring at both extremes of the soil pH range (see Fig. 17:2) the question arises as to the range in soil reaction in which minimum fixation occurs. The basic iron and aluminum phosphates have a minimum solubility around pH 3 to 4. At higher pH values some of the phosphorus is released and the fixing capacity is somewhat reduced. Even at pH 6.5, however, much of the phosphorus is still probably chemically combined with iron and aluminum.[14] As the pH approaches 6 precipitation as calcium compounds begins and at pH 6.5 the formation of insoluble calcium salts is a factor in rendering the phosphorus unavailable. Above pH 7.0 even more insoluble compounds such as apatites are formed.

These facts seem to indicate that maximum phosphate availability to plants is obtained when the soil pH is maintained in the range from 6.0 to 7.0. (See Fig. 17:2.) Even in this range, however, the fact should be emphasized that phosphate availability may still be very low and that added soluble phosphates are readily fixed by soils. The low recovery (perhaps 10–30 per cent) by plants of added phosphates in a given season is partially due to this fixation.

17:10. PHOSPHORUS FIXING POWER OF SOILS

In light of the above discussion it is interesting to note the actual quantity of phosphorus which soils are capable of fixing. Data from three

Table 17:3. The Phosphorus Adsorbing Power of Three New Jersey Soils Limed and Unlimed Expressed as Pounds of 20 Per Cent Superphosphate per Acre-Furrow-Slice[15]

Soil	*Treatment*	*pH*	*P-fixing Power, Lbs. 20% Super/A.F.S.*
Sassafras	No lime	3.6	28,400
Sassafras	lime	6.5	13,916
Collington	No lime	3.2	93,720
Collington	lime	6.5	50,268
Dutchess	No lime	3.8	68,728
Dutchess	lime	6.5	44,020

[14] Swenson, R. M., V. C. Cole, and D. H. Sieling, "Fixation of Phosphate by Iron and Aluminum and Replacement by Organic and Inorganic Ions," *Soil Sci.*, 67: 3–22, 1949.

[15] From Toth, S. J., and F. E. Bear, "Phosphorus-Adsorbing Capacities of Some New Jersey Soils," *Soil Sci.*, 64: 199–211, 1947.

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[15] From Toth, S. J., and F. E. Bear, "Phosphorus-Adsorbing Capacities of Some New Jersey Soils," *Soil Sci.*, 64: 199–211, 1947.

sources of phosphorus.[17] Apparently the phytin is absorbed directly by the plants, while the nucleic acids probably are broken down by enzymes at the root surfaces and the phosphorus is absorbed in either the organic or inorganic form. In spite of the readiness with which these compounds may be assimilated, however, plants commonly suffer from phosphor deficiency even in the presence of considerable quantities of organic forms of this element. Just as with the inorganic phosphates the problem is one of availability.

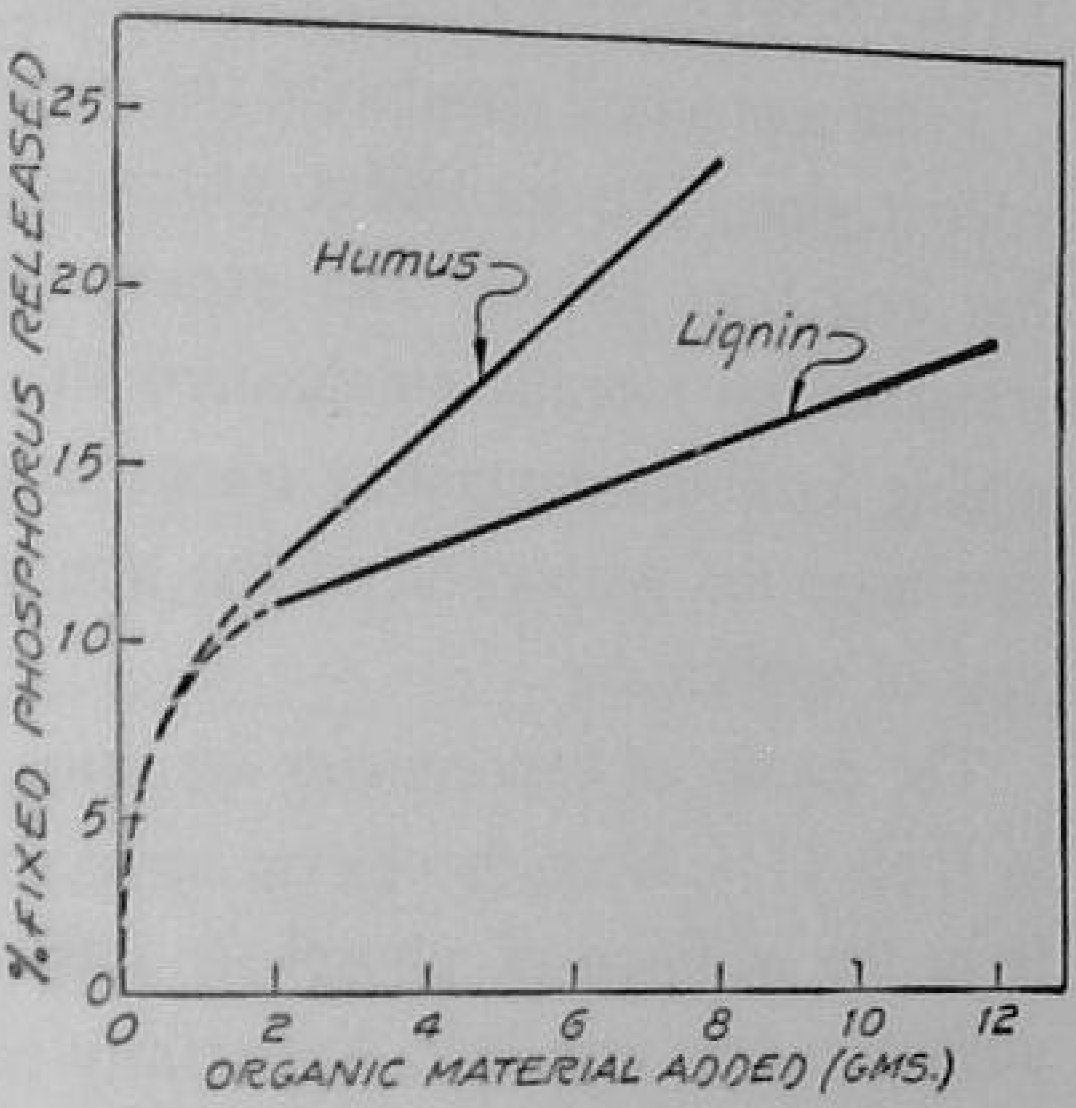


FIG. 17:3. *The effect of added organic materials on the release of phosphorus previously fixed by iron compounds. Both humus and lignin are effective, the humus to the greater degree. These results suggest that mineral fixation of phosphorus may be lower in soils comparatively high in organic matter. (See footnote 14, page 481.)*

Phytin behaves in the soil much as do the inorganic phosphates,[18] forming iron, aluminum and calcium phytates. In acid soils the phytin is rendered insoluble and thus unavailable because of reaction with iron and aluminum. Under alkaline conditions calcium phytate is precipitated and the phosphorus carried is likewise rendered unavailable.

The fixation of nucleic acids involves an entirely different mechanism, but the end result—low phosphorus availability—is the same. Apparently nucleic acids are strongly adsorbed by clays, especially montmorillonite. This adsorption is particularly pronounced under acid conditions and results in a marked decrease in the rate of decomposition of the nucleic acids. Consequently, the available phosphorus supply from this source is low, especially in acid soils which contain appreciable amounts of montmorillonite.

The judicious application of lime to acid soils is thus fully as important in organic phosphorus nutrition as it is in rendering inorganic compounds

[17] Rogers, H. T., R. W. Pearson, and W. H. Pierre, "Absorption of Organic Phosphorus by Corn and Tomato Plants and the Mineralizing Action of Exo-enzyme Systems of Growing Roots," *Proc. Soil Sci. Soc. Amer.*, 5: 285–291, 1941.

[18] For a discussion of the factors affecting the availability of organic phosphorus compounds, see Bower, C. A., *Studies on the Forms and Availability of Soil Organic Phosphorus*, Iowa Agr. Exp. Sta. Res. Bul. 362, Aug. 1949.

available. Whether we are dealing with inorganic soil phosphates, added fertilizers, or organic materials the importance of lime as a controlling factor in phosphate availability is clearly evident.

17:13. PRACTICAL CONTROL OF PHOSPHORUS AVAILABILITY

From a practical standpoint the phosphorus utilization picture is not too encouraging. The inefficient utilization of applied phosphates by plants has long been known. The experimental use of radioactive phosphorus materials has recently emphasized this point even more thoroughly.[19] By adding fertilizers containing traceable phosphorus it has been possible to determine the proportion of the applied phosphates absorbed during the year of application.

The results of experiments on corn, soybeans and potatoes are shown in Table 17:4. Even though on some soils marked responses were obtained from the addition of phosphate fertilizers, the efficiency of phosphorus utilization was very low. Apparently maximum yields were obtained only by supplying much more phosphorus than the plants absorbed in a given season.

Table 17:4. The Recovery of Applied Fertilizer Phosphates During the First Crop Year[20]

Soil	*Crop*	*Percentage of Fertilizer Phosphorus Recovered the First Year*
Bladen	Corn	11.8[21]
Bladen	Potatoes	7.6[21]
Bladen	Soybeans	18.2[21]
Webster	Corn	6.5[22]
Clarion	Corn	3.4[23]

Liming and placement of fertilizers. The small amount of control that can be exerted over phosphate availability seems to be associated with

[19] The entire August, 1949, issue of *Soil Science* (Vol. 68: 113–202) is devoted to reports of field experiments which were designed to give information on the efficiency of phosphorus utilization.

[20] Bladen data calculated from Krantz, B. A., W. L. Nelson, C. D. Welch, and N. S. Hall, "A Comparison of Phosphorus Utilization by Crops," *Soil Sci.*, 68: 171–178, 1949.

The other data are from Stanford, G., and L. B. Nelson, "Utilization of Phosphorus as Affected by Placement: I Corn in Iowa," *Soil Sci.*, 68: 129–136, 1949.

[21] Average 2 locations and 2 application rates.

[22] Average 2 locations, 5 methods of application.

[23] One location, average 5 methods of application.

liming, fertilizer placement and *organic matter maintenance*. By holding the pH of soils between 6.0 and 7.0 the phosphate fixation can be kept at a minimum. (See Figs. 14:4 and 17:2.) In order to prevent rapid reaction of phosphate fertilizers with the soil these materials are commonly placed in localized bands. In addition phosphatic fertilizers are quite often pelleted or aggregated to retard still more their contact with the soil. The effective utilization of phosphorus in combination with barnyard manure is evidence of the importance of organic matter in increasing the availability of this element.

In spite of the above precautions a major portion of the added phosphates still reverts to less available forms (see Fig. 17:1). It should be remembered, however, that the reverted phosphorus is not lost from the soil and through the years undoubtedly is slowly available to growing plants. This becomes an important factor especially on soils which have been heavily phosphated for years.

17:14. POTASSIUM—THE THIRD "FERTILIZER" ELEMENT

The history of fertilizer usage in the United States shows that nitrogen and phosphorus received most of the attention when commercial fertilizers first appeared on the market. Although the role played by potassium in plant nutrition has long been known, the importance of potash fertilization has received full recognition only in comparatively recent years.

The reasons that a widespread deficiency of this element did not develop until recently are at least twofold. Firstly, the supply of available potassium originally was so high in most soils that it took many years of cropping for a serious depletion to appear. Secondly, even though the potassium in certain soils may have been insufficient for optimum crop yields, production was much more drastically limited by a lack of nitrogen and phosphorus. With an increased usage of fertilizers carrying these latter elements, crop yields have been correspondingly increased. As a consequence, the draft on soil potassium has been greatly augmented. This, coupled with considerable loss by leaching, has enhanced the demand for potassium to the point that its usage in commercial fertilizers now exceeds that of nitrogen and rivals that of phosphorus.

17:15. EFFECTS OF POTASSIUM ON PLANT GROWTH [24]

The presence of adequate available potassium in the soil has much to do with the general tone and vigor of the plants grown. Moreover, by increasing crop resistance to certain diseases and by encouraging the root system, potassium tends to counteract the ill effects of too much nitrogen. In delaying maturity potassium works against undue ripening influences of phosphorus. In a general way, it exerts a balancing effect on both nitrogen and phosphorus, and consequently is especially important in a mixed fertilizer.

Potassium is essential for starch formation and the translocation of sugars. It is necessary in the development of chlorophyl, although it does not, like magnesium, enter prominently into its molecular structure. This element is important to cereals in grain formation, giving plump heavy kernels. Abundant available potassium also is absolutely necessary for tuber development. Consequently, the percentage of this element usually is comparatively high in mixed fertilizers recommended for potatoes. In fact, all root crops respond to liberal applications of potassium. As with phosphorus, it may be present in large quantities in the soil and yet exert no harmful effect on the crop.

The leaves of crops suffering from a potassium deficiency [25] appear dry and scorched at the edges, while the surfaces are irregularly chlorotic. With such plants as red and alsike clover, alfalfa, and sweet clover, these symptoms are preceded by the appearance of small dots arranged more or less regularly around the edges of the leaves. As a result of such deterioration photosynthesis is much impaired and the synthesis of starch practically brought to a standstill.

17:16. THE POTASSIUM PROBLEM

Availability of potassium. In contrast to the situation as regards phosphorus, most mineral soils, except those of a sandy nature, are compara-

[24] As pointed out in Chapter 2 (footnote 6, page 22), sodium has been found to partially take the place of potassium in the nutrition of certain plants. When there is a deficiency of potash, the native sodium of the soil, or that added in such fertilizers as nitrate of soda, may be very useful.

[25] For the deficiency symptoms of potassium, see *Potash Deficiency Symptoms,* distributed by The American Potash Institute, Washington, D. C., 1937.

See also *Hunger Signs in Crops,* American Society of Agronomy and the National Fertilizer Association, Washington, D. C., 1949; and *If They Could Speak,* Chilean Nitrate Educational Bureau, New York, 1941.

tively high in *total* potassium. In fact, the total quantity of this element is generally greater than that of any other major nutrient element. Amounts as great as 40,000 to 60,000 pounds of K_2O per acre furrow-slice are not at all uncommon. (See page 26.) Yet the quantity of potassium held in an easily exchangeable condition at any one time often is very small. Most of this element is held rigidly as part of the primary minerals or is fixed in forms that are at best only moderately available to plants. Also competition by microorganisms for this element contributes at least temporarily to its unavailability to higher plants.[26] Thus, the situation in respect to potassium utilization parallels that of phosphorus and nitrogen in at least one respect. A very large proportion of all three of these elements in the soil is insoluble and relatively unavailable to growing plants.

Leaching losses. Unlike the situation in respect to nitrogen and particularly phosphorus, however, much potassium is lost by leaching. An examination of the drainage water from mineral soils on which rather liberal fertilizer applications have been made will usually show considerable quantities of potash. In extreme cases, the magnitude of this loss may approach that of potash removal by the crop. For example, heavily fertilized sandy soils on which crops such as vegetables or tobacco are grown may suffer serious losses by leaching. Even on a representative humid region soil receiving only moderate rates of fertilizer, the annual loss of potash by leaching is usually about 20 pounds per acre. (See table 9:5, page 249.)

Crop removal. The third phase of the potassium problem concerns the concentration of this element in plants, or in other words, its removal by growing crops. Under ordinary field conditions and with an adequate nutrient supply, potassium removal by crops is high, often being 3–4 times that of phosphorus and equaling that of nitrogen. The removal of 75 to 100 pounds K_2O per acre by a 16 ton silage corn crop is not at all unusual. Moreover, this situation is made even more critical by the fact that plants tend to take up soluble potassium far in excess of their needs if sufficiently large quantities are present. This tendency is termed *luxury consumption* since the excess potassium absorbed apparently does not increase crop yields to any extent.

Examples of luxury consumption. The principles involved in luxury consumption are shown by the graph of Figure 17:4. For many crops there is a more or less direct relationship between the available potassium in the

[26] Jenny, Hans, and E. R. Shade, "The Potassium-Lime Problem in Soils," *Jour. Amer. Soc. Agron.*, 26: 162–170, 1934.

soil and the removal of this element by plants. The available potassium would, of course, include both that added and that already present. A certain amount of this element is needed for optimum yields and this is termed *required potassium.* All potassium above this critical level is considered as a *luxury,* the removal of which is decidedly wasteful.

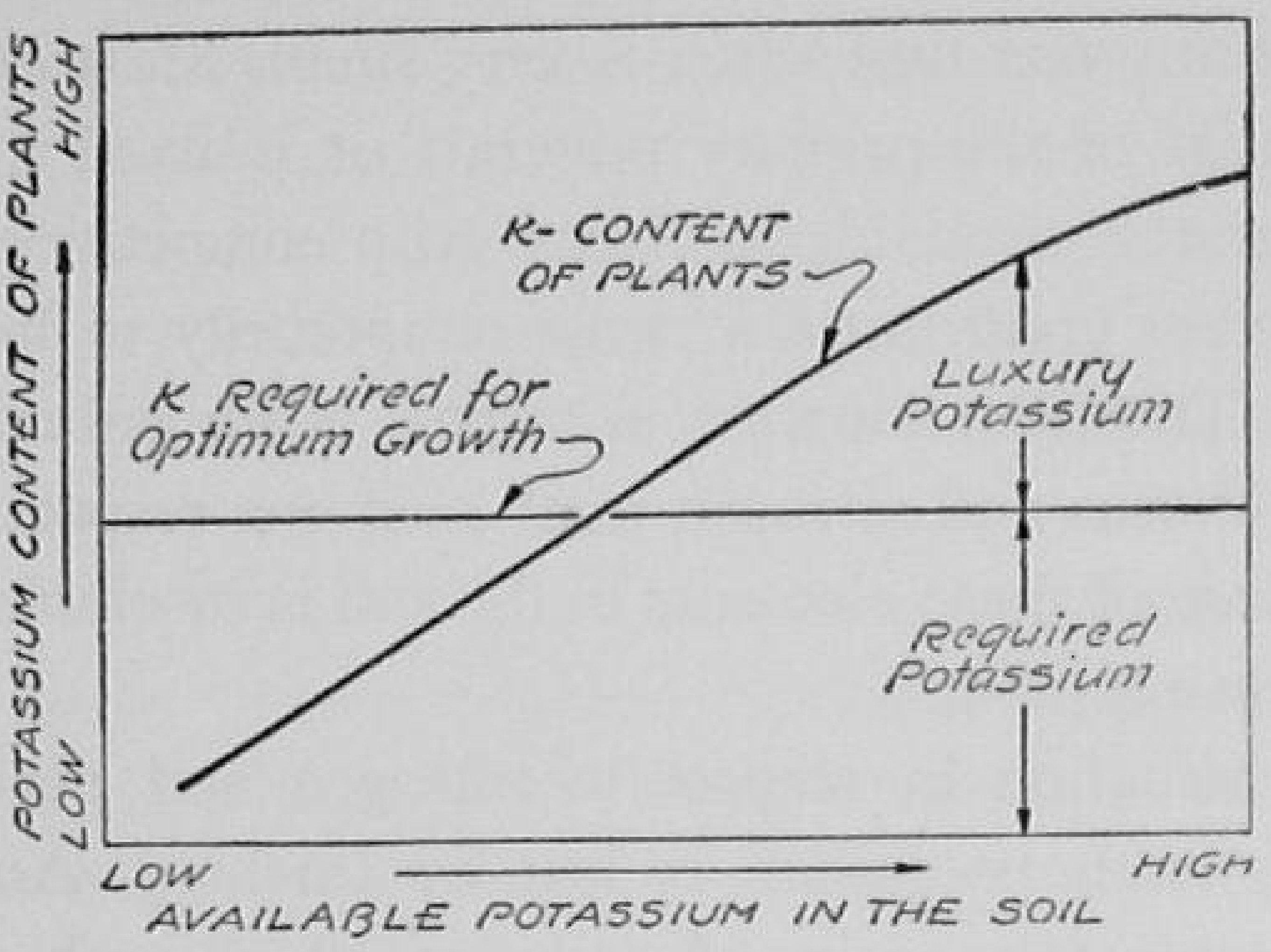


FIG. 17:4. *A schematic diagram showing the general relationship between the potassium content of plants and the available soil potassium. If excess quantities of potash fertilizers are applied to a soil, the plants will absorb potassium in excess of that required for optimum yields. This luxury consumption may be wasteful, especially if the crops are completely removed from the soil.*

Under field conditions luxury consumption becomes particularly serious. For example, to save labor a person may be tempted to supply potassium (a) only once in a 3 or 4 year rotation, or (b) during the first year of a 3 or 4 year perennial hay crop. Much of the potassium thus added is likely to be wastefully absorbed by the first crop of the rotation sequence, or in the case of the hay, even in the first cutting. Consequently, little of the added potassium would remain for subsequent crops.

In summary then the problem of potassium economy in its most general terms is at least threefold: (a) a very large proportion of this element at a given time is relatively unavailable to higher plants; (b) due to the solubility of its available forms, it is subject to wasteful leaching losses; and (c) the removal of this element by crop plants is high, especially when luxury quantities of this element are supplied. With these ideas as a background let us now consider the various forms of potassium in soils and their availabilities.

17:17. FORMS AND AVAILABILITY OF POTASSIUM IN SOILS

For convenience of study, the various forms of potassium in soils can be classified on the basis of availability in three general groups: (a) *unavailable,* (b) *readily available,* and (c) *slowly available.* Although most of the soil potassium is in the first of these three forms, from an immediate practical standpoint the latter two are undoubtedly of greater significance.

The relationship among these three general categories is shown diagrammatically in Figure 17:5. Equilibrium tendencies presented therein are of vital practical importance, especially when we are dealing with the slowly and readily available forms. A slow change from one form to another can and does occur. This makes possible a fixation and conservation of added soluble potassium and a subsequent slow release of this element when the readily available supply is reduced.

Relatively unavailable forms. By far the greatest part (perhaps 90–98 per cent) of all soil potassium in a mineral soil is in relatively unavailable forms. (See Fig. 17:5.) The compounds containing most of this form of potassium are the feldspars and the micas. These minerals are quite resistant to weathering and probably supply relatively insignificant quantities of potassium during a given growing season.[27] However, their accumulative contribution from year to year to the over-all available potassium in the soil undoubtedly is of considerable importance. Potassium is gradually released to more available forms through the action of solvents such as

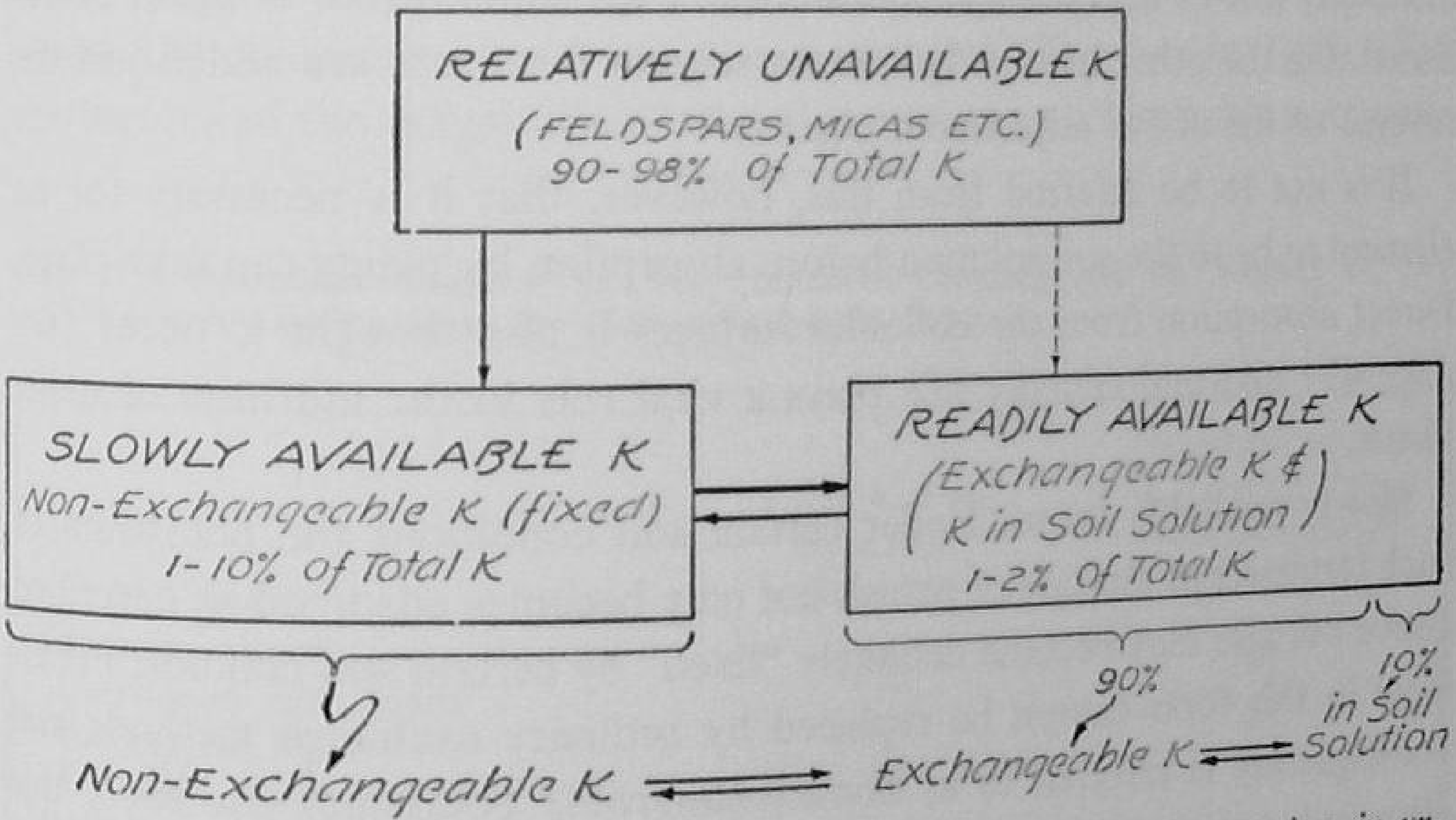


FIG. 17:5. *Diagram showing the relative proportions of the total soil potassium in unavailable, slowly available, and readily available forms respectively. Only 1 to 2 per cent is rated as readily available. Of this, approximately 90 per cent is exchangeable and only 10 per cent appears in the soil solution at any time.*

Even higher values (11–18 per cent) have been obtained for so-called non-exchangeable colloid potassium. See Wood, L. K., and E. E. DeTurk, "The Absorption of Potassium in Soils in Non-replaceable Forms," Proc. Soil Sci. Soc. Amer., *5:152–161, 1940.*

The figures quoted are modified from Attoe, O. J., and E. Truog, "Exchangeable and Acid Soluble Potassium as Regards Availability and Reciprocal Relationships," Proc. Soil Sci. Soc. Amer., *10:81–86, 1945.*

[27] See Graham, E. R., and H. C. Turley, "Soil Development and Plant Nutrition III. The Transfer of Potassium from the Non-Available Form as Reflected by the Growth and Composition of Soybeans," *Proc. Soil Sci. Soc. Amer.*, 12: 332–335, 1947.

carbonated water. Also, the presence of acid clay is of some significance in the breakdown of these primary minerals with the subsequent release of potassium and other bases. (See page 300.)

Readily available forms. The readily available potassium constitutes only about 1 or 2 per cent of the total amount of this element in an average mineral soil. It exists in soils in two forms: (a) potassium in the soil solution and (b) exchangeable potassium adsorbed on the soil colloidal surfaces. Although most of this available potassium is in the exchangeable form (approximately 90 per cent), soil solution potassium is somewhat more readily absorbed by higher plants and is, of course, subject to considerable leaching loss. (See page 487.)

As represented in Figure 17:5, these two forms of readily available potassium are in dynamic equilibrium. Such a situation is extremely important from a practical standpoint. To begin with, absorption of soil solution potassium by plants results in a temporary disruption of the equilibrium. Then, to restore the balance, some of the exchangeable potassium immediately moves into the soil solution until the equilibrium is again established. On the other hand, when water soluble fertilizers are added just the reverse of the above adjustment occurs.

It is not to be inferred from this, however, that it is necessary for an element to be in the soil solution before absorption by plants can take place. Direct absorption from the colloidal surfaces is also thought to occur (see page 43) and undoubtedly this plays a vital role in the nutrition of many plants.

Slowly available forms. Under certain soil conditions the potassium of such fertilizers as muriate of potash not only becomes adsorbed as described above but also may become definitely "fixed" by certain soil colloids. Potassium in this form cannot be replaced by ordinary exchange methods and consequently is referred to as *non-exchangeable* potassium. As such, this element is not readily available to higher plants. This form is in equilibrium, however, with the available forms and consequently acts as an extremely important reservoir of slowly available potassium. The entire equilibrium may be represented as follows.[28] (See Fig. 17:5.)

$$\text{Non-exchangeable K} \rightleftharpoons \text{Exchangeable K} \rightleftharpoons \text{Soil solution K}$$

The importance of the adjustment shown above to practical agriculture should not be overlooked. It is of special value in the conservation of added

[28] Peech, M., and R. Bradfield, "The Effect of Lime and Magnesia on the Soil Potassium and on the Absorption of Potassium by Plants," *Soil Sci.*, 55: 37–48, 1943.

potassium. For example, most potash-containing fertilizers are added at planting time and are usually applied in localized bands. Immediately upon dissolving, a large proportion of the soluble (soil solution) potassium becomes attached to the colloids. As a result, the above equilibria shift to the left and some exchangeable ions are converted to the non-exchangeable form. Although this renders more potassium at least temporarily unavailable, the over-all effect apparently is beneficial. In this form the potassium is not subject to leaching and thus a significant conservation is attained. Also, since the fixed potassium is slowly reconverted to the available forms later, it is by no means completely lost to growing plants.

Release of fixed potassium. The above reaction is perhaps of even greater practical importance in another way. The quantity of non-exchangeable or "fixed" potassium in some soils is quite large. (See legend of Figure 17:5.) The fixed potassium in such soils is continually released to the exchangeable form in amounts large enough to be of great practical importance. For example, Bray and DeTurk [29] found a release of as much as 288 pounds of potassium per acre from an Illinois soil in a 6 month period. Other similar results have been observed. The data in Table 17:5 give an idea of the magnitude of the release of non-exchangeable potassium

Table 17:5. Potassium Removal by Very Intensive Cropping and the Amount of This Element Coming from the Non-exchangeable Form

Soil	*Total K Used by Crops* (Lbs./A)	*Percentage of the K Coming from Non-exchangeable Form*
Wisconsin soils: [30]		
Carrington silt loam	119	75
Spencer silt loam	59	80
Plainfield sand	88	25
Mississippi soils: [31]		
Robinsonville f.s.l.	108	33
Houston clay	57	47
Ruston sandy loam	42	24

[29] Bray, R. H., and E. E. DeTurk, "The Release of Potassium from Non-Replaceable Forms in Illinois Soils," *Proc. Soil Sci. Soc. Amer.*, 3: 101–106, 1939.

[30] Average of six consecutive cuttings of Ladino clover, from Evans, C. E., and O. J. Attoe, "Potassium Supplying Power of Virgin and Cropped Soils," *Soil Sci.*, 66: 323–334, 1948.

[31] Average of eight consecutive crops of millet, from Gholston, L. E., and C. D. Hoover, "The Release of Exchangeable and Non-exchangeable Potassium from Several Mississippi and Alabama Soils upon Continuous Cropping," *Proc. Soil Sci. Soc. Amer.*, 13: 116–121, 1948.

from certain soils. In several cases cited the potassium removed by crops was largely supplied from non-exchangeable forms.

17:18. FACTORS AFFECTING POTASSIUM FIXATION IN SOILS[32]

Although the exact mechanism or mechanisms that govern potassium fixation and release are not clearly understood, it is definitely known that several soil conditions markedly influence the amounts fixed. Among the factors are: (a) the nature of the soil colloids, (b) wetting and drying, (c) freezing and thawing and (d) the presence of excess lime. These will be considered briefly in turn.

The effects of colloids, moisture and temperature. The ability of the various soil colloids to fix potassium varies widely. For example, kaolinite and soils in which this clay mineral is dominant fix little potassium. On the other hand, clays of the 2:1 type such as montmorillonite and illite fix potassium very readily and in large amounts.

The mechanism for potash fixation is probably not the same for all minerals. Montmorillonite and similar minerals, for example, apparently fix this element appreciably only upon drying. This has been explained[33] by assuming an entrapment of potassium ions between the contracting structural units (see Fig. 4:4) as the soil dries. Some release of the ions thus held occurs upon rewetting, but the liberation is rather slow.

Under moist conditions fixation is apparently due to micaceous minerals such as illite. The exact manner by which potassium is changed in these minerals from an exchangeable to a fixed, non-exchangeable cation is not known. However, it is quite possible that the potassium migrates into the interior of colloidal crystals, and there becomes an integral part of the lattice structure.

Alternate freezing and thawing has been shown to result in the release of fixed potassium under certain conditions.[34] Although the practical importance of this is recognized, the mechanism by means of which it occurs is not as yet understood.

[32] See Levine, A. K., and J. S. Joffe, "Fixation of Potassium in Relation to Exchange Capacity of Soils. V. Mechanism of Fixation," *Soil Sci.*, 53: 407–416, 1947. See also Stanford, George, "Fixation of Potassium in Soils Under Moist Conditions and on Drying in Relation to Type of Clay Mineral," *Proc. Soil Sci. Soc. Amer.*, 12: 167–171, 1947; and Wear, J. I., and J. L. White, "Potassium Fixing in Clay Minerals as Related to Crystal Structure," *Soil Sci.*, 71: 1–14, 1951.

[33] Page, J. B., and L. D. Baver, "Ionic Size in Relation to Fixation of Cations by Colloidal Clay," *Proc. Soil Sci. Soc. Amer.*, 4: 150–155, 1940.

[34] Fine, L. O., T. A. Bailey, and E. Truog, "Availability of Fixed Potassium as Influenced by Freezing and Thawing," *Proc. Soil Sci. Soc. Amer.*, 5: 183–190, 1940.

Influence of lime. Applications of lime often result in an increase in the potassium fixing power of soils.[35] Under normal liming conditions this may be more beneficial than detrimental due to the conservation of the potassium so affected. Thus, potassium in well limed soils is not as likely to be leached as drastically as is that in acid soils. This is illustrated by data in Table 17:6.

Table 17:6. The Effect of Percentage Base Saturation on the Leaching Losses of Exchangeable Potassium from a Creedmore Coarse Sandy Loam[36]

Soil pH	*Base Saturation (%)*	*Exchangeable Potassium Lost by Leaching (% of Total)*
4.83	28	70
5.30	40	49
5.63	50	26
7.03	72	16

The sandy soil studied was limed to increase the base saturation from 28 to 72 per cent. When 6.2 inches of water were percolated through the original soil (28 per cent base saturation), about 70 per cent of the exchangeable potassium was removed. The limed sample (72 per cent base saturation) when similarly treated sustained a potassium loss of only 16 per cent. The effect of lime in preventing potash loss undoubtedly is of considerable practical import in many cases.

There are conditions, however, under which the effects of lime on the availability of potash are so drastic as to become quite undesirable.[37] For example, in certain soils potassium deficiency is apparently due to the presence of excess calcium carbonate. The unavailability of potassium in such soils is thought to be due in some way to lime induced fixation.

17:19. TWO PRACTICAL IMPLICATIONS IN RESPECT TO POTASSIUM

Frequency of application. One very important suggestion that is evident from the facts thus far considered is that frequent light applications of

[35] The effect of lime on potash fixation was reviewed by Peech, M., and R. Bradfield, "Effect of Lime and Magnesia on the Soil Potassium and on the Absorption of Potassium by Plants," *Soil Sci.*, 55: 37–48, 1943.

[36] From Baver, L. D., "Practical Applications of Potassium Interrelationships in Soils and Plants," *Soil Sci.*, 55: 121–126, 1943.

[37] See Allaway, H., and W. H. Pierre, "Availability, Fixation and Liberation of Potassium in High-lime Soils," *Jour. Amer. Soc. Agron.*, 31: 940–953, 1939.

potassium are usually superior to heavier and less frequent ones. Such a conclusion is unavoidable when we consider the luxury consumption by crops, the ease with which this element is lost by leaching, and the fact that excess potassium is subject to fixation. Although the latter phenomenon has definite conserving features, these are in most cases entirely outweighed by the disadvantages of leaching and luxury consumption.

The K supplying power of soils. A second very important suggestion of practical significance is that full advantage should be taken of the potash supplying power of soils. The idea that each pound of potassium removed by plants or through leaching must be returned in fertilizers may not always be correct. In some soils the large quantities of moderately available forms already present can be utilized. Where slowly available forms are not found in significant quantities, however, supplementary additions are frequently necessary. Moreover, the importance of lime in reducing leaching losses of potassium should not be overlooked as a means of effectively utilizing the power of soils to furnish this element.

In this chapter and the one preceding, the factors affecting the supplies of nitrogen, phosphorus, and potassium available to growing plants have been considered. We have dealt mostly with those reactions taking place within the soil which determine in part the amounts of these elements that plants have at their disposal. We are now ready to discuss means of supplementing the natural supply of these elements. Let us begin by considering commercial fertilizers, our main outside source of these and other nutrient constituents.

CHAPTER

18 Fertilizers and Fertilizer Management

WHILE THE use of animal excrement on cultivated soils was common as far back as agricultural records can be traced, mineral salts have been systematically and extensively employed for the encouragement of crop growth hardly more than one hundred years. They are now an economic necessity on many soils. Any inorganic salt, such as nitrate of soda, or an organic substance, such as castor meal or fish scrap, regularly on the market and applied to the soil to promote crop development is considered to be a commercial fertilizer.[1]

18:1. THE FERTILIZER ELEMENTS

There are at least eleven essential nutrient elements that plants obtain from the soil. Two of these, calcium and magnesium, are applied as lime in regions where they are deficient. Although not usually rated as a fertilizer, lime does exert a profound nutritive effect. Sulfur is present in several commercial fertilizers and its influence is considered important. It is not critical nutritionally except in certain localities, however, and consequently receives only secondary attention as a fertilizer. This leaves three nutrients other than the trace elements—*nitrogen, phosphorus,* and *potassium.* And since they are so commonly applied in commercial fertilizers they are often referred to as *the fertilizer elements.*

[1] For further information as to fertilizers and their use, see Gustafson, A. F., *Handbook of Fertilizers,* Orange Judd Publishing Company, Inc., New York, 1939.
Worthen, E. L., *Farm Soils, Their Management and Fertilization,* John Wiley and Sons, Inc., New York, 1941.
Collings, G. H., *Commercial Fertilizers,* The Blakiston Company, Philadelphia, 1947.
Bear, Firman E., *Theory and Practice in the Use of Fertilizers,* John Wiley and Sons, Inc., New York, 1938.

18:2. THE NUTRIENT BALANCE

Before taking up a discussion of the various fertilizing materials, one point should be emphasized most emphatically. The three fertilizer elements, when properly used, not only tend to check, balance, support, and supplement one another but the other nutrient elements as well. These relationships are very important in fertilizer practice since they have much to do with the economy and effectiveness of fertilizers.

Ideally, the elements added should so supplement the nutrients already in the soil as to present to the plant just the correct proportion of available nitrogen, phosphorus, and potassium. At the same time the amounts and availability of the other essential elements should be ideal. In short, the fertility balance as a whole should be such as to produce a large and normal crop growth.

In practice, however, such an ideal is difficult to attain. The soil is always more or less an unknown quality as to the seasonal availability of its constituents. Moreover, it is difficult to forecast the reactions that will occur when the fertilizer contacts the soil. The influence of calcium, magnesium, manganese, iron, aluminum, and other elements upon the effectiveness of a fertilizer is always problematical.

18:3. THREE GROUPS OF FERTILIZER MATERIALS

The emphasis which has been placed on the three nutrient elements leads directly to a very simple grouping of the fertilizer materials. On the basis of the elements supplied, they automatically fall into three groups: (1) those that supply nitrogen, (2) those serving as a source of available phosphoric acid, and (3) those carrying water-soluble potash.

The classification, however, is not so simple as this grouping would imply, as several fertilizer materials carry two of the elements of nutrition. As examples of this overlapping, potassium nitrate and ammoniated superphosphate may be cited. The situation will be fully apparent when the fertilizer tables presented later are examined and the compounding of mixed goods considered.

Because of the lack of space it will only be possible to discuss each of the three groups in a general way, listing the various fertilizers of each, and mentioning the outstanding characteristics of the more important. Fortunately, detailed descriptions of the various fertilizers and their prop-

erties are available in published form [2] if the reader cares to go further than these pages will carry him.

If the reader is already familiar with the individual fertilizer materials or does not wish to consider them at this point, he may omit sections 18:4 to 18:8 inclusive and continue the question of fertilizers and fertilizer practice with section 18:9 (page 508).

18:4. NITROGEN CARRIERS—TWO GROUPS

Often referred to as *ammoniates,* nitrogen fertilizers may be divided for convenience into two groups: (1) *organic* and (2) *inorganic.* These groups are so different both as to source and chemical and physical properties that they are best discussed separately. Let us begin first with the organic ammoniates.

18:5. ORGANIC NITROGEN CARRIERS

The organic fertilizers, among which are garbage tankage, fish scrap, castor pomace, and cocoa meal (see Table 18:1), must undergo aminization, ammonification, and nitrification before their nitrogen becomes fully available to higher plants. As a result, they are not so quickly effective as nitrate of soda, ammonium nitrate or sulfate of ammonia, and do not produce a suitable crop response unless the soil is warm. Their action, however, is mild and natural.

Organic fertilizers are used in many cases because they tend to liberate their nitrogen gradually throughout the season. Also they aid in maintaining a good physical condition in any fertilizer mixture of which they may be a part. This conditioning influence is important as it assures a ready drillability of the mixture. Mixed fertilizers are often supplied with from 200 to 300 pounds per ton of some organic material for this reason.

The main objection to the organic ammoniates is the cost of the nitrogen carried, which is three to five times as much as that supplied as nitrate of soda, sulfate of ammonia, or other inorganics. Some of the organic ammoniates listed in Table 18:1 are too expensive for general use. Those that are most commonly employed are starred.

18:6. INORGANIC NITROGEN CARRIERS

General consideration. There are many inorganic carriers which are used to supply nitrogen in mixed fertilizers. The most important of these, together with their compositions and sources, are listed in Table 18:2. Fortunately, there is a wide range in the nitrogen contents of these materials—from 3 per cent in ammoniated superphosphate to 82 per cent in anhydrous ammonia. Also, several chemical forms are represented, including ammonium and nitrate compounds as well as materials such as urea and cyanamid. Both of the latter upon

[2] See references cited at bottom of page 495.

Table 18:1. Organic Ammoniates [3]

Fertilizer	*Source*	*Per Cent Nitrogen*
Dried blood	Packing house	8 to 12
Animal tankage	Packing house	5 to 10 (3 to 13% P_2O_5)
Meat meal	Packing house	10 to 11 (1 to 5% P_2O_5)
Garbage tankage *	Steam-treated garbage, grease removed	2 to 4 (some P_2O_5 and K_2O)
Process tankage *	Waste treated with acid under steam	6 to 10 (some P_2O_5)
Sewage sludge *	Sludge dried and ground	5 to 6 (variable amounts of P_2O_5 and K_2O)
Dried fish scrap *	Cannery waste and non-edible fish	6 to 10 (4 to 8% P_2O_5)
Cottonseed meal	Ground cake after removal of oil	6 to 9 (2 to 3% P_2O_5 and 1 to 2% K_2O)
Linseed meal	Ground cake after removal of oil	4 to 5 (1.5% P_2O_5 and 1.5% K_2O)
Tobacco stems *	Waste tobacco, midribs and stems	1.5 to 3.5 (4 to 9% K_2O)
Castor meal *	Ground cake after removal of oil	5 to 7 (about 2% P_2O_5 and 1% K_2O)
Cocoa-cake meal *	Ground cake refuse	3.5 to 4.5 (some P_2O_5 and K_2O)

hydrolysis in the soil yield NH_4-ions which can be taken up by plants or can be oxidized to nitrates. Although all the materials listed are used as nitrogen carriers, the ammonium and nitrate containing compounds are employed most widely.

The materials listed in Table 18:2 have one thing in common—they can all be produced synthetically starting with atmospheric nitrogen. This fact has far reaching significance, especially in respect to future nitrogen utilization. In the first place, it means that the quantity of nitrogen available to produce these compounds is limited only by the quantity present in the atmosphere.

Secondly, synthetic methods of supplying nitrogen have played a significant role in reducing the cost of this element, historically so much more expensive than either potassium or phosphorus. In addition, synthetic processes have yielded a wide variety of materials in large enough quantities to make their usage practical. Such a variety was not possible when natural deposits alone were depended upon.

As a result of these and other features, synthetic nitrogen carriers are assuming more and more importance. Considerably more than two-thirds of

[3] The materials at present cheap enough to be used in the compounding of mixed fertilizers are starred.

Table 18:2. **Inorganic Nitrogen Carriers**

Fertilizer	*Chemical Form*	*Source*	*Approximate Per Cent Nitrogen*
1. Sodium nitrate	$NaNO_3$	Chile saltpetre and synthetic	16
2. Ammonium sulfate	$(NH_4)_2SO_4$	By-product from coke and gas, and also synthetic	21
3. Ammonium nitrate [4]	NH_4NO_3	Synthetic	33
4. "Cal-nitro" and "A.N.L." [4]	NH_4NO_3 & dolomite	"	20
5. Urea [5]	$CO(NH_2)_2$	"	42
6. Calcium cyanamid [6]	$CaCN_2$	"	22
7. Anhydrous ammonia [7]	Liquid NH_3	"	82
8. Ammonia liquor	dilute NH_4OH	"	25
9. Nitrogen solutions	NH_4NO_3 in NH_4OH or Urea in NH_4OH	"	37–45
10. Ammoniated superphosphate [8]	$NH_4H_2PO_4$, $(NH_4)_2SO_4$ plus calcium phosphates	"	3 or 4 (16–18% P_2O_5)
11. Ammo-phos [9]	$NH_4H_2PO_4$ and other ammonium salts	"	11 (48% P_2O_5)

the fertilizer nitrogen used in the United States today is carried by synthetics. Their methods of manufacture are worthy of brief consideration.

Ammonia and its solutions. Perhaps the most important of the synthetic processes is that in which ammonia gas is formed from the elements hydrogen and nitrogen. This may be represented as follows:

$$N_2 + 3\ H_2 \longrightarrow 2\ NH_3$$

This reaction is extremely important since it yields a compound which is at the present time the least expensive of any listed in Table 18:2. Of equal importance is the fact that this is the first step in the formation of many other synthetic compounds.

[4] Deliquescence controlled by surface coating materials or by mixing with dolomite, as in the case of "Cal-nitro" and "A.N.L." (trade names).

[5] The commercial compound is treated with a finely ground drier to control deliquescence.

[6] This fertilizer contains over 25 per cent $Ca(OH)_2$ and about 13 per cent carbon besides other ingredients such as $CaCO_3$, CaS, etc. The total amount of calcium expressed as CaO is approximately 53 per cent.

[7] The cheapest form of nitrogen for fertilizer use now available.

[8] Made by treating ordinary superphosphate with ammonia liquor or anhydrous ammonia. May also contain urea or nitrate nitrogen.

[9] Manufactured by treating ammonia with phosphoric acid

$$NH_3 + H_3PO_4 \longrightarrow NH_4H_2PO_4$$

The ammonia gas formed in the above reaction is utilized in at least three ways. Firstly, it may be liquefied under pressure yielding anhydrous ammonia. (See Table 18:2.) This material is employed in the production of ammoniated superphosphate and mixed fertilizers, in addition to being used as a separate material for direct application. (See page 522.) Secondly, ammonia gas may be dissolved in water yielding NH_4OH. This is often used alone (ammonia liquor) or more frequently as a solvent for other nitrogen carriers such as NH_4NO_3 and urea, to give the so-called "nitrogen solutions" (Figure 18:1). In recent years these solutions have become increasingly popular and now furnish a high proportion of the nitrogen in commercial fertilizers. The factor which limits their usage in even larger quantities is the tendency of these materials to depress phosphate availability.[10]

A third very important use of ammonia gas is in the manufacture of other inorganic nitrogen fertilizer materials. The reactions by means of which some fertilizer compounds are produced synthetically from ammonia are shown diagrammatically in Figure 18:1. A careful study of this diagram will be very helpful in establishing the relationship between ammonia and the materials derived synthetically from it. These substances will be considered briefly.

Sulfate of ammonia. Sulfate of ammonia is produced synthetically as shown in Figure 18:1.[11] This material has long been one of the most important nitrogen carriers, especially in the manufacture of mixed fertilizers. Its nitrogen is somewhat cheaper than that carried by nitrate of soda, and consequently it has been used extensively as a top dressing material. Under favorable conditions the NH_4-ions nitrify readily, thus increasing the ease of nitrogen utilization. Its use is most satisfactory on soils well supplied with lime.

Sodium and ammonium nitrates. Nitric acid, the manufacture of which is possible from oxidized ammonia, is used in making both ammonium and sodium nitrates. Ammonium nitrate which has the advantages of supplying both NH_4- and NO_3-ions, has been employed in increasing quantities in the past few years. When used as a separate material, this salt is best supplied in the form of pellets which are suitably coated or otherwise treated to reduce its deliquescence. It must always be remembered that this fertilizer is a hazard in case of fire because of its explosive properties. The percentage of nitrogen in ammonium nitrate carriers ranges from 20 per cent for "Cal-nitro" and "A.N.L." to perhaps 33 per cent for the higher grades of ammonium nitrate (Table 18:2).

In addition to the synthetic source mentioned above, sodium nitrate is obtained as a natural product, saltpetre, from salt beds in Chile. In fact, before

[10] Both anhydrous ammonia and the "nitrogen solutions" reduce the availability of phosphorus in fertilizers if too large quantities of these materials are used. The effect of adding too much of the nitrogen compounds is to bring about reversion of the phosphorus to $Ca_3(PO_4)_2$, in which form it is not considered easily available to plants. (See footnote 16, page 503.)

[11] Much of the NH_3 used in the production of $(NH_4)_2SO_4$ is a by-product of coke manufacture. Sulfate of ammonia obtained from this source is termed "by-product" in contrast to the "synthetic" cited in Figure 18:1.

the coming of synthetics, Chilean nitrate of soda represented essentially the sole source of this compound.

Sodium nitrate has long been one of the main inorganic sources of commercial nitrogen and still continues popular. It supplies nitrogen in a form that immediately stimulates many crops even if the soil is cold. Hence, it is extremely valuable early in the spring and as a side-dressing later in the season.

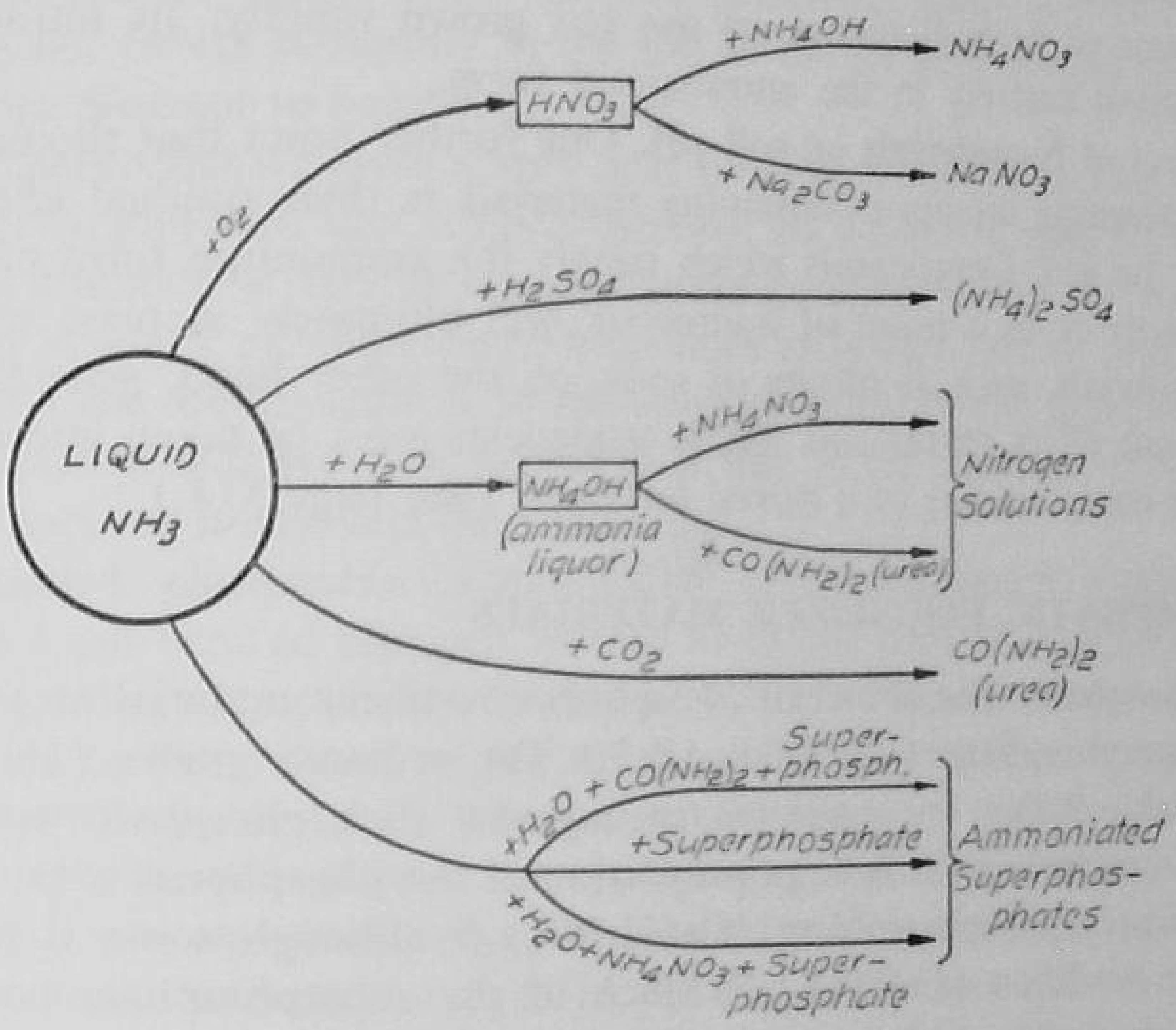


FIG. 18:1. *Diagram showing how various fertilizer materials may be synthesized from ammonia. This gas is obtained as a by-product of coke manufacture and, in even larger quantities, by direct synthesis from elemental nitrogen and hydrogen. In recent years, NH_3 and the other synthetic materials shown above have supplied most of our fertilizer nitrogen.*

Other synthetic nitrogen carriers. Another promising synthetic is urea, a fertilizer containing almost three times as much nitrogen as nitrate of soda. It readily undergoes hydrolysis in the soil, producing ammonium carbonate.[12] Thus, the immediate effect of this fertilizer is towards alkalinity although its residual influence tends to lower soil pH. The ammonium carbonate produced is ideal for rapid nitrification, especially if exchangeable bases are present in adequate amounts. Urea thus ultimately presents both NH_4-ions and NO_3-ions for plant absorption. Its one serious objection, high deliquescence, has been largely overcome by coating its particles with dry powders.

Calcium cyanamid, another synthetic product of some importance, has two objections as a fertilizer. When used to top-dress crops it may cause injury to the foliage if not carefully applied. This is less likely to occur if the pelleted,

[12] $CO(NH_2)_2 + 2\,H_2O \longrightarrow (NH_4)_2CO_3$

rather than the powdered form is used. In the soil its nitrogen changes rather readily to ammonium carbonate but there are certain temporary intermediate products that may be harmful to crops.

Of the synthetics carrying phosphorus in addition to nitrogen, ammoniated superphosphate is the most used in the United States although Ammo-phos is quite popular when it is available. Since most soils respond to both nitrogen and phosphorus and since ammoniated superphosphate is a comparatively cheap source of both elements, its use has grown rapidly. Its nitrogen, however, is almost entirely in the ammoniacal form.

The effect of N-materials on soil pH. One further point that should be mentioned concerning nitrogen containing materials is their residual effect on the acidity of the soil. Compounds which supply the ammonium form of nitrogen, either directly or as a result of hydrolysis, will ultimately increase soil acidity. Nitrate materials, such as nitrate of soda, on the other hand, generally have a residual basic effect on the soil. These tendencies must be taken into consideration in the compounding of a mixed fertilizer. (See page 513.)

18:7. PHOSPHATIC FERTILIZER MATERIALS

Superphosphate. The principal phosphorus fertilizer material at the present time is superphosphate. (See Table 18:3.) The ordinary grades (16 to 21 per cent available P_2O_5) are made by treating raw rock phosphate with suitable amounts of sulfuric acid. A large proportion of the phosphorus is thus changed to the primary phosphate form ($Ca(H_2PO_4)_2$) although some is left in the secondary condition ($CaHPO_4$).[13] Much of the superphosphate now used is this ordinary grade, which consists of about 31 per cent phosphates, 50 per cent gypsum, and 19 per cent impurities of various kinds. The total *phosphorus* to the hundred weight is rather low, ranging from 7 to 9 pounds, while the sulfur and calcium amount to about 12 and 18 pounds respectively.

There are two grades of high-analysis superphosphates, the *double* (32 per cent available P_2O_5) and the *treble* (40–47 per cent available P_2O_5). They differ from the ordinary types principally in that they contain more phosphorus and less gypsum, the two varying more or less inversely with each other. The amount of calcium sulfate in the treble superphosphate is almost negligible.[14]

[13] Representing the complex raw rock by the simple formula $Ca_3(PO_4)_2$, the following conventional reactions may be used to show the changes that occur during the manufacture of ordinary 16 to 21 per cent superphosphate.

$$\underset{\text{(Insoluble)}}{Ca_3(PO_4)_2} + 2\,H_2SO_4 \longrightarrow \underset{\text{(Water Soluble)}}{Ca(H_2PO_4)_2} + 2\,CaSO_4 + \text{impurities}$$

The acid is never added in amounts capable of completing this reaction. Consequently, some secondary phosphate—$CaHPO_4$, spoken of as *citrate soluble phosphoric acid,* is produced.

$$\underset{\text{(Insoluble)}}{Ca_3(PO_4)_2} + H_2SO_4 \longrightarrow 2\,CaHPO_4 + CaSO_4 + \text{impurities}$$

[14] The *treble* superphosphate is synthesized by treating a high grade phosphate rock with phosphoric acid:

$$Ca_3(PO_4)_2 + 4\,H_3PO_4 \longrightarrow 3\,Ca(H_2PO_4)_2 + \text{impurities}$$

Of the three superphosphates, the ordinary grade (16 to 21 per cent available P_2O_5) is by far the most commonly used. And since much of it goes into mixed fertilizers or is ammoniated, the finely ground, rather than the granulated materials are in demand. The former gives more uniform mixtures, and does not segregate when handled as does the granulated. Moreover, it is contacted more readily by the ammonia when ammoniated superphosphate is made. But when superphosphate is to be applied separately to the soil or is used to reinforce farm manure (page 543) the well granulated type is preferable. This form does not revert as rapidly in the soil as do the finer grades and in addition is more pleasant to handle.

Since superphosphate gives a very acid reaction when tested with indicators, it is generally supposed that it must increase the acidity of soils to which it is added. As a matter of fact, it has practically no effect within the ordinary pH range. But at a low pH superphosphate tends to reduce acidity, while at a pH of 7.5 to 8.5 the modification is in the other direction.[15] The slight influence of this fertilizer on soil reaction probably is due to the vigorous reversion that occurs as soon as it contacts the soil.

Ammoniated phosphates. Ammoniated superphosphate,[16] which contains from 3 to 4 per cent of nitrogen and 16 to 18 per cent of phosphoric acid, is gradually gaining in popularity. It affords a chance of easily changing ammonia to a suitable fertilizer form, at the same time improving the physical qualities of the superphosphate itself. When a small amount of nitrogen can be used profitably with the phosphorus, the application of this fertilizer is to be recommended as it is a cheap and effective source for both nutrients.

Ammo-phos, which may analyze 11 per cent of nitrogen and 48 per cent of phosphoric acid, is also an economical fertilizer when it can be obtained and should be used when a larger proportion of nitrogen to phosphoric acid than is supplied by ammoniated superphosphate, is desired. (See Table 18:3.)

The *double* superphosphate may be made by mixing ordinary superphosphate and the treble in the proper amounts. It contains about one-half as much gypsum as do the ordinary grades.

[15] Pierre, W. H., "The Effect of Mono-, Di-, and Tri-Calcium Phosphates on the Reaction of Soils of Different Degrees of Acidity," *Jour. Amer. Soc. Agron.*, 26: 278–289, 1924.

[16] Ammoniated superphosphate is made by treating ordinary superphosphate with either ammonia liquor or anhydrous ammonia. The ammonia is thus changed to forms suitable for fertilizer use and the physical condition of the superphosphate improved. The reactions are as follows:

$$Ca(H_2PO_4)_2 + NH_3 \longrightarrow NH_4H_2PO_4 + CaHPO_4$$

$$2\,CaHPO_4 + CaSO_4 + 2\,NH_3 \longrightarrow Ca_3(PO_4)_2 + (NH_4)_2SO_4$$

When enough ammonia has been added to give 2 per cent of nitrogen in the mixture, practically all of the monocalcium phosphate has been reverted. At this stage the nitrogen is present in two different forms and the phosphorus in three. All of these are considered as readily available to plants except $Ca_3(PO_4)_2$.

The percentage of nitrogen in ammoniated superphosphate may be readily doubled by using an ammonia liquor enriched by adding urea or ammonium nitrate. A third form of nitrogen may thus be present in the final product.

Basic slag and bone meal. Basic slag, while commonly used in Europe, is on the market only to a limited extent in the United States. Because of the alkalinity and the rather ready availability of its phosphoric acid, it is a very desirable phosphatic fertilizer. It seems to be especially effective on acid soils apparently because of its high content of calcium hydroxide.

Table 18:3. Phosphoric-acid Carriers

Fertilizer	*Chemical Form*	*Source*	*Approximate Percentage of Available* P_2O_5
Superphosphates	$Ca(H_2PO_4)_2$ and $CaHPO_4$	Made from rock phosphate	16–47
Ammoniated superphosphate	$NH_4H_2PO_4$, $CaHPO_4$, $Ca_3(PO_4)_2$, $(NH_4)_2SO_4$	Synthesized	16–18 (3–4% N)
Ammo-phos	$NH_4H_2PO_4$ mostly	Synthesized [17]	48 (11% N)
Basic slag [18]	$(CaO)_5 \cdot P_2O_5 \cdot SiO_2$	Steel slag	15–25
Bone black	$Ca_3(PO_4)_2$	Refining refuse	32–35
Raw bone meal	$Ca_3(PO_4)_2$	Packing house	20–25
Steamed bone meal [19]	$Ca_3(PO_4)_2$	Packing house	23–30
Rock phosphate	Fluor- and Chlor-apatites	Ground rock	25–30
Monocalcium phosphate	$Ca(H_2PO_4)_2$	Synthesized [20]	50
Calcium metaphosphate	$Ca(PO_3)_2$	Synthesized [21]	62–63

Bone meal is an expensive form of phosphoric acid. Moreover, it is rather slowly available in the soil. It is used extensively in greenhouse and floricultural work, part of its popularity possibly being due to the nitrogen carried. Bone meal can be applied in large amounts and yet produce no detrimental influence on crop growth. This is not so likely to be the case, of course, with some of the more readily soluble phosphatic fertilizers.

[17] Made with phosphoric acid and ammonia:

$$H_3PO_4 + NH_4OH \longrightarrow NH_4H_2PO_4 + H_2O + \text{impurities.}$$

[18] The formula of this fertilizer is very uncertain. Basic slag is intensely alkaline because of the presence of large amounts of the hydroxide and carbonate of lime.

[19] The steamed bone meal is cooked under pressure and the fat and oil removed. The bone is left open and porous.

[20] Made by treating a high-analysis rock phosphate with H_3PO_4:

$$Ca_3(PO_4)_2 + 4\,H_3PO_4 \longrightarrow 3\,Ca(H_2PO_4)_2 + \text{impurities.}$$

[21] Synthesized from rock phosphate or limestone and P_2O_5:

$$Ca_3(PO_4)_2 + 2\,P_2O_5 \longrightarrow 3\,Ca(PO_3)_2 + \text{impurities, or}$$

$$CaCO_3 + P_2O_5 \longrightarrow Ca(PO_3)_2 + CO_2 + \text{impurities.}$$

Rock phosphate. Raw rock phosphate, due to its insolubility, must be finely ground in order that it may react at all readily when applied to the soil. Its availability is markedly increased by the presence of decaying organic matter. For that reason it is often recommended as a reinforcement for farm manure, liberal amounts being used. Ordinarily it should not be applied alone unless the soil is rather well supplied with active organic matter.

Rock phosphate is the least available of the phosphatic fertilizers already mentioned, the order being: superphosphate and ammo-phos, basic slag, bone meal, and raw rock. Although its chemical formula is given conventionally as $Ca_3(PO_4)_2$, rock phosphate is much more complicated than this formula would suggest. It apparently approaches the fluorapatite ($3\ Ca_3(PO_4)_2 \cdot CaF_2$) in its molecular make-up. (See page 475.) This, no doubt, accounts in part for its slow availability.

Considerable discussion at one time arose regarding the relative merits of superphosphate and raw rock phosphate. Thorne,[22] after a critical review of the field experiments where these two materials were compared, came to the conclusion that superphosphate is generally somewhat superior. He found that, while raw rock may be employed with profit on land materially deficient in phosphorus, superphosphate has generally proved the more effective and the more economical carrier of phosphoric acid for crops.

These conclusions, which are amply corroborated by other investigators, do not imply that raw rock phosphate is never equal or superior to superphosphate, nor that raw rock may not have a place as a fertilizer on many farms especially those near the phosphate fields. To a soil rich in organic matter it may be added to advantage. It is especially useful in reinforcing farm manure, seemingly being about as effective under such conditions as is superphosphate. However, the trend in fertilizer manufacture seems to be such that raw rock phosphate will continue to be used largely as a source of phosphorus for the manufacture of other and more soluble forms.

High analysis phosphates. Mention should be made of two very high analysis phosphate fertilizers not as yet in general use—mono-calcium phosphate [$Ca(H_2PO_4)_2$—about 50 per cent available P_2O_4] and calcium metaphosphate [$Ca(PO_3)_2$—62–63 per cent available P_2O_5]. (See Table 18:3.) Both are more or less in the experimental stage but hold great promise as they seem to be as effective, when used in equivalent amounts, as superphosphate. Their concentrations make them extremely attractive when transportation is a factor.

The mono-calcium phosphate is synthesized by applying phosphoric acid to high grade phosphate rock. (See Table 18:3, note 20.) The $Ca(PO_3)_2$, commonly called *meta-phos*, may be made by treating either phosphate rock or limestone with phosphorus pentoxide. (Table 18:3, Note 21.) The highly concentrated P_2O_5 can be produced at the mine, shipped to a point where lime-

[22] Thorne, C. E., *Raw Phosphate Rock as a Fertilizer*, Bul. 305, Ohio Agr. Exp. Sta., 1916.
See also Bauer, F. C., *et al.*, *Effects of Soil Treatment on Soil Productivity*, Bul. 516: 124–130, Ill. Agr. Exp. Sta., 1945.

stone is cheaply available, and the meta-phos manufactured in the territory where it is to be used. Transportation costs are thus cut to a minimum.

Classification of phosphate fertilizers. For purposes of evaluation and sale the various phosphorus compounds that are present in phosphatic fertilizers are classified in an arbitrary yet rather satisfactory way as follows (Table 18:4):

Table 18:4. Fertilizer Classification of Phosphates

1. *Water-soluble*	$Ca(H_2PO_4)_2$ $NH_4H_2PO_4$ K phosphate	*Available* phosphoric acid [23]
2. *Citrate-soluble* In 15 per cent neutral ammonium citrate—$CaHPO_4$ In 2 per cent solution of citric acid —phosphates of basic slag		
3. *Insoluble* Phosphate of bone and raw phosphate rock		*Unavailable* phosphoric acid [23]

It is well to note that the classification of the phosphates is in some degree artificial as well as arbitrary. For instance, *available* phosphates, because of the reversion that occurs, are not strictly available once they contact the soil. The term *available* really refers to those phosphates that readily stimulate plant growth. Those phosphates that are less effective are rated as currently *unavailable,* yet in the soil they may eventually supply a certain amount of phosphorus to crops.

Suppose in the case of ordinary superphosphate that the guarantee is 20 per cent available P_2O_5. The term available phosphoric acid is here used in the sense explained above and includes both the water soluble $Ca(H_2PO_4)_2$ and the citrate soluble $CaHPO_4$. With ammo-phos (11 per cent total nitrogen and 48 per cent available P_2O_5) the available phosphoric acid is carried by the water-soluble $NH_4H_2PO_4$. Since phosphate fertilizers are guaranteed in the terms set forth above, it is absolutely necessary that a person be familiar with the distinctions noted. Otherwise, a correct interpretation of a guarantee is impossible.

18:8. FERTILIZER MATERIALS CARRYING POTASSIUM

One of the largest known deposits of potassium salts occurs in Germany, where there are extensive beds varying from 50 to 150 feet in thickness, lying under an area stretching from the Harz Mountains to the Elbe River. It is

[23] The various fertilizers studied are grouped as follows:
Available—superphosphate (all grades), ammoniated superphosphate, ammo-phos, basic slag, mono-calcium phosphate, meta-phos.
Mostly unavailable—rock phosphate and bone meal.

known as the Strassfurt deposits. Crude potash salts occur in other sections of Germany, in France, in the United States, and elsewhere.

While potash deposits are found in other parts of the world, the French, German, and American mines are at present the only ones operating extensively. The first World War stimulated considerable investigation regarding possible sources of potash, especially in the United States. Domestic underground deposits and saline brines now furnish most of the potash used in America.

Kainit and manure salts (see Table 18:5) are the most common of the crude potash sources. The high grade chloride and sulfate of potash originally imported from Germany and France are their refined equivalents. The potassium chloride, now used so extensively in the United States, comes mostly from underground deposits, saline brines, and old lake beds found in this country.

Table 18:5. Potash Fertilizer Materials

Fertilizer	*Chemical Form*	*Percentage of K_2O*
Potassium chloride [24]	KCl	48–60
Potassium sulfate	K_2SO_4	48–50
Sulfate of potash-magnesia [25]	Double salt of K and Mg	25–30
Manure salts	KCl mostly	20–30
Kainit	KCl mostly	12–16
Potassium nitrate [26]	KNO_3	44 (and 13% N)
Potassium phosphate [26]	Indefinite	30–50 (and 32–53% P_2O_5)
Wood ashes [27]	K_2CO_3 largely	3–7 (and 1–2% P_2O_5)
Tobacco stems [28]	Organic	4–9 (and 2–4% N)

All potash salts used as fertilizers are water-soluble and are therefore rated as readily available. Unlike nitrogen salts, most potassium fertilizers, even if employed in large amounts, have little or no effect on the soil pH. Some discrimination is made, however, against potassium chloride (muriate) in respect to potatoes and especially tobacco since large dosages are considered to lower the quality. Hence, when large amounts of potash are to be applied for the latter crop, the major part usually is preferred in the sulfate form.

Potassium-magnesium sulfate, although rather low in potash, has attained considerable usage in parts of this country where magnesium is likely to be

[24] All of these fertilizers contain other potash salts than those listed.
[25] Contains 25 per cent of $MgSO_4$ and some chlorine.
[26] Little used at present.
[27] Wood ashes are alkaline, often intensely so. The other potash fertilizers are neutral or slightly alkaline.
[28] For other organics carrying potash, see Table 18:1.

deficient. In some respects it is a more desirable source of magnesia than is dolomitic limestone or dolomite.

Tobacco stems, as well as other potassium-carrying organics, are used in making mixed goods (see page 498) and are important as a filler and drier. In some parts of the country wood ashes are sometimes obtainable. They carry their potassium largely in the carbonate form, a combination especially desirable for certain crops. The amount of lime added with wood ashes is usually large and on an acid soil may have a considerable influence.

18:9. SULFUR IN SOIL FERTILIZATION [29]

In examining the sulfur problem in humid regions it will be found that for a representative farm soil the total loss of sulfur (erosion, leaching, and crop removal combined) perhaps falls within the range of 20 to 30 pounds an acre yearly. (See Tables 9:5, page 249 and 9:8, page 267.) This deficiency is met in several ways.

Consider first the addition of sulfur in rain and snow.[30] The amount depends, of course, upon location, ranging from 2 or 3 pounds of combined sulfur an acre a year to perhaps over 100 pounds near industrial centers. Since the influence of industrial centers is extremely local, it is hardly safe in general to assume that this source will fully meet the deficit (20 to 30 pounds yearly per acre) already set up.

In general and dairying farming the problem is taken care of in a more or less automatic way. In practical soil management sulfur is returned to the soil in green manures, crop residues, and farm manures. Commercial fertilizers, such as superphosphate, ammonium sulfate, and potassium sulfate [31] contain considerable amounts of sulfur and are now commonly used. An application to the acre of 10 tons of farm manure reinforced with 500 pounds of ordinary superphosphate adds well over 100 pounds of

[29] *Soil Science,* Vol. 70, No. 1, July, 1950, carries a sulfur symposium of nine well-documented papers which cover most of the phases relating to sulfur as a fertilizer.

[30] Wilson, B. D., "Sulfur Supplied to the Soil in Rainwater," *Jour. Amer. Soc. Agron.,* 18: 1108–1112, 1926.

Alway, F. J., "A Nutrient Element Slighted in Agricultural Research," *Jour. Amer. Soc. Agron.,* 32: 913–921, 1940.

Bertramson, B. R., *et al.,* "Sulfur Studies of Indiana Soils and Crops," *Soil Sci.,* 70: 27–41, 1950.

[31] The amount of sulfur in a ton of farm manure perhaps averages about 5 lb. Ordinary superphosphate and commercial ammonium sulfate and potassium sulfate contain to the hundred-weight approximately 12, 24, and 15 lb. respectively. See Mehring, H. L., and G. A. Bennett, "Sulfur in Fertilizers, Manures and Soil Amendments," *Soil Sci.,* 70: 73–81, 1950.

sulfur. This alone, once during the rotation, would go far toward meeting any deficit.

There is another angle to the sulfur problem that until a few years ago escaped attention—the probability that the soil, and perhaps to a lesser degree higher plants, absorb sulfur dioxide from the atmosphere. Alway,[32] who advanced the idea, substantiates his suggestions rather conclusively. The magnitude of this absorption, which, bear in mind, is exclusive of the sulfur added in precipitation, probably is in excess of that brought down by rain, snow, and dust. Bertramson places it at 27 pounds an acre a year for Indiana soils.[33] Here, then, is another automatic addition, a further insurance against a sulfur deficiency. And incidentally it furnishes a second reason why crops requiring large amounts of sulfur, such as alfalfa, can be grown successfully on land receiving no artificial applications of this element.

In the light of the information available, it seems that the sulfur situation is not comparable with, nor so serious as that of phosphorus. With certain soils in eastern Washington and Oregon, in Minnesota, and in California, sulfur in some form undoubtedly must be added artificially, especially in the growing of alfalfa and sweet clover. However, under ordinary conditions, if the normal residues produced on the farm are utilized, there seems little reason for sulfur being a limiting factor in soil productivity, especially if fertilizers carrying sulfur are used.[34]

18:10. TRACE ELEMENTS AS FERTILIZERS[35]

Of the elements usually found in mere traces in soil and used but sparingly by plants, the application of four most frequently gives beneficial results. These elements are copper, manganese, zinc, and boron. With iron, which exists in most soils in large amounts (page 26), the situation usually is not urgent except in overlimed humid region soils and in alkaline soils of arid regions.

[32] Alway, F. J., A. W. Marsh, and W. J. Methley, "Sufficiency of Atmospheric Sulfur for Maximum Crop Yields," *Proc. Soil Sci. Soc. Amer.*, 2: 229–238, 1937.

[33] Bertramson, B. R., *et al.*, "Sulfur Studies of Indiana Soils and Crops," *Soil Sci.*, 70: 27–41, 1950.

[34] Bertramson and his associates (*op. cit.*) draw the same general conclusion from a sulfur balance sheet on Indiana soils.

[35] The literature dealing with the trace elements is exceedingly voluminous. See Willis, L. G., *Bibliography of References to the Literature on the Minor Elements and Their Relation to the Science of Plant Nutrition*, 4th ed., Vol. 1, 1948, Chilean Nitrate Educational Bureau, New York.

The reason for the deficiency of the four trace elements listed, either individually or in mass, is not difficult to postulate. In the *first* place, not only are they ordinarily present in the soil in extremely minute amounts (page 25) but also their availability is uncertain, a slight change in soil conditions, especially in respect to pH (see Fig. 14:4), being sufficient to render them critical. For instance, overliming is likely to reduce their availability often to the danger point. (See page 438.)

In the *second* place, practically no attention in the past has been paid to the trace elements in our systems of soil management. It is only in recent years that the essential nature of these constituents has been known. And even then it apparently was assumed that the amounts used by plants were too small to be important or that the elements were incidentally applied in sufficient quantities to forestall any deficiency. We know now that such ideas were fallacious.

A deficiency diagnosis usually is made from plant symptoms [36] rather than from soil analysis since a fluctuation in availability that is difficult to measure analytically, may determine whether or not the trace element is critical. Already crop specialists are adept in the detection of various deficiencies, while the growers themselves are rapidly becoming familiar with the symptoms that their particular crops are likely to exhibit.

The influence of overliming in accentuating or actually in creating a trace-element deficiency has already been mentioned. (See page 403.) Its effects in respect to manganese, and perhaps copper and zinc also, probably are the result of precipitation, the rise in pH above 7 tending to produce compounds that are unavailable to higher plants.

As to the lime-boron relationship, there is a considerable difference of opinion.[37] Some authors claim that, although the soil untreated and the lime alone do not individually reduce the boron solubility to any extent, the two in combination fix it markedly. Others feel that the large amounts of active calcium influence the plant in such a way physiologically as to interfere either with the entrance of boron or its utilization once it has been absorbed. Still others suggest that lime stimulates microbial activity and thereby raises a competition for boron that seriously affects the crop. A biochemical competition may perhaps similarily affect manganese, copper and zinc. But whatever the explanation, it would seem that overliming

[36] See *Hunger Signs in Crops,* American Society of Agronomy and National Fertilizer Association, Washington, D. C., 1948; and *If They Could Speak,* Chilean Nitrate Educational Bureau, New York, 1941.

[37] For citations see bottom of page 403.

should especially be guarded against where trace-element deficiencies are suspected.

When a trace-element deficiency is to be corrected, especially if the case is urgent, a salt of the lacking nutrient usually is added separately to the soil. Copper, manganese, and zinc generally are supplied as the sulfate while boron is applied as borax. The rate of application should be carefully regulated as an overdose can cause severe injury. For instance, 50 pounds of borax an acre are nearing the maximum for the average soil when its pH is near 7. Much, of course, depends upon the crop grown.[38] In case of doubt as to the amounts to apply, expert advice should be sought.

In some cases trace elements, especially boron, are placed in ordinary commercial fertilizers and their presence therein stated in the guarantee. A stock mixture is compounded using some organic ammoniate as a base to which is added the desired trace-element salts. A few pounds of this mixture are included in each ton of the fertilizer. The idea, of course, is to insure against a possible deficiency of the trace elements. One objection to such a practice is that not enough of any one trace element may be added to the soil to adequately meet a real deficiency should it occur. Furthermore, the amount of trace element applied varies with the dosage of the commercial fertilizer. Trace elements usually require a more careful regulation than can be attained in this way.

That the fertilization with trace elements is of great practical importance cannot be denied. Plant malnutritions, due to such deficiencies, are becoming more and more apparent. All kinds of plants are affected. The next few years, undoubtedly, will see a tremendous development of this phase of fertility regulation.

18:11. MIXED FERTILIZERS

For years fertilizer manufacturers have placed on the market mixtures of materials which contain at least two of the so-called "fertilizer elements," and usually all three. The former are designated as *incomplete* fertilizers while the latter are spoken of as *complete*. In either case materials such as those discussed in previous sections are mixed in proper proportions to furnish the desired amount of the nutrient elements. For example, an ammonia solution, superphosphate, muriate of potash and a small amount

[38] Powers, W. L., and J. V. Jordan, "Boron in Oregon Soils and Plant Nutrition," *Soil Sci.*, 70: 99–107, 1950.

of an organic such as castor pomace might be used if a complete fertilizer is desired.

Physical condition. In addition to supplying nitrogen, phosphorus, and potassium in desired proportions, however, a commercial fertilizer should have certain other properties. Of utmost importance in this regard is the *physical condition* of the mixed goods. The fertilizer should be drillable when first purchased and should remain in this condition after storage. Mixtures of certain materials cannot be used because of their tendency to "set up" or harden. Of the fertilizer materials commonly found in mixed goods, ammonium and sodium nitrates, sulfate of ammonia and potassium chloride are most likely to develop unsatisfactory physical conditions. Improperly cured superphosphate may also give trouble. The extreme deliquescence of some of the salts, especially ammonium nitrate, tends to make mixed fertilizers sticky and thus reduce the drillability.

Methods of insuring free flowage. The free flowing condition of a mixed fertilizer is maintained by two important procedures: (1) Moisture resistant bags are commonly used in distribution and (2) certain moisture absorbing materials are usually included in the fertilizer mix. In the latter case, organic ammoniates such as castor pomace, tobacco stems and dried poultry manure are especially valuable. Dolomitic limestone used to counteract the acid developing tendencies of certain fertilizers also acts as a conditioner. The manufacturer is as careful regarding the drillability of his product as he is in respect to the maintenance of its guaranteed analysis. Many complete fertilizers carry as much as 300 lbs. a ton of materials that will help insure a suitable physical condition.

Another method of encouraging the free flowing of fertilizers is that of granulating the goods after mixing.[39] Separate materials such as sodium and ammonium nitrates have been pelleted for several years to prevent caking. In recent years the granulation of small but steadily increasing amounts of mixed fertilizers has taken place in this country.

In addition to having free flowing properties, granulated fertilizers present certain other advantages. For example, they are less disagreeable to handle since they are comparatively free of small dustlike particles. The granulation also prevents the fertilizer from being carried by the wind and retards its reaction with the soil.

[39] See Taylor, R. P., "Mechanics of Mixed Fertilizer Production," a chapter in *Amer. Soc. Agron. Monograph*, No. 3, 1942.

18:12. EFFECT OF MIXED FERTILIZERS ON SOIL pH

Acid forming fertilizers. Most complete fertilizers, unless specially treated, tend to develop an acid residue in soils. This is mainly due to the influence of certain of the nitrogen carriers, especially those of an ammoniacal nature. The major effect of NH_4-ions is exerted when they are nitrified. Upon oxidation the ammonium compounds tend to increase acidity as shown by the following reaction:

$$NH_4^+ + 2O_2 \longrightarrow 2H^+ + NO_3^+ + H_2O$$

Two other effects of NH_4-ions are important, but to a lesser extent, in decreasing soil pH. For example, when ammonium sulfate is added to a soil, some of the NH_4-ions are readily adsorbed by the soil colloidal matter replacing equivalent quantities of other cations. If Ca- and M-ions are displaced their loss by leaching is encouraged. This ultimately may result in a lowering of soil pH. On the other hand, if H-ions are displaced sulfuric acid appears in the soil solution. A similar development of sulfuric acid occurs if higher plants or microorganisms use the ammonium radical of the fertilizer to a greater extent than they do the sulfate.

In addition to ammonium compounds, materials such as urea and some of the organics, which upon hydrolysis yield ammonium ions, are potential sources of acidity. The phosphorus and potash fertilizers commonly used have little effect upon soil pH unless they also contain nitrogen.

Non-acid forming fertilizers. For many years no particular attention was paid to this acid forming tendency of certain fertilizer materials. For instance, the average mixed fertilizer sold in the United States in 1933 had an acidity equivalent per ton of about 150 pounds of calcium carbonate.[40] Although this has been reduced to some extent, the average mixed fertilizer is still rather acid in effect.[41]

In many instances, however, this acid forming tendency is completely counteracted by adding dolomitic limestone to the mixture. Such fertilizers are termed *neutral* or *non-acid forming* and exert little residual effect on soil pH. Data are available in respect to nitrogen fertilizers that make it

[40] Mehring, A. L., and A. J. Peterson, "The Equivalent Physiological Acidity or Basicity of American Fertilizers," *Jour. Assoc. Official Agr. Chemists*, 17: 95–100, 1934.

[41] Mehring, A. L., "Fertilizers for Special Use," a chapter in *Amer. Soc. Agron. Monograph* No. 3, 1952.

rather easy to calculate the approximate amount of dolomitic limestone necessary in any particular case.[42]

18:13. THE FERTILIZER GUARANTEE

Every fertilizing material, whether it is a single carrier or a complete ready-to-apply mixture, must carry a guarantee as to its content of nutrient elements. The exact form is generally determined by the state in which the fertilizer is offered for sale. The *total nitrogen* is usually expressed in its *elemental form* (N). The phosphorus is quoted in terms of *available phosphoric acid* (P_2O_5), while the potassium is stated as *water soluble potash* (K_2O).

The guarantee of a simple fertilizer, such as sulfate of ammonia, is easy to interpret, since the name and the composition of the material is printed on the bag or tag. When the amount of the nutrient element carried is noted, the purity of the fertilizer can usually be ascertained if a person is at all familiar with the compounds present. For instance, if the material is nitrate of soda containing 16 per cent total nitrogen, it is apparent that the fertilizer is high-grade, since *chemically pure* sodium nitrate contains only slightly more than 16 per cent nitrogen.

The interpretation of an analysis of a complete fertilizer is almost as easy. The simplest form of guarantee is a mere statement of the relative amounts of N, P_2O_5, and K_2O. Thus, a 5–10–10 fertilizer contains 5 per cent *total nitrogen,* 10 per cent *available phosphoric acid,* and 10 per cent *water-soluble potash.* In some states, figures as to *water-soluble nitrogen, water-insoluble nitrogen,* and *available insoluble nitrogen* are required by law.

An *open formula* guarantee is used by some companies. Such a guarantee not only gives the usual chemical analysis but also a list of the various

[42] See Pierre, W. H., "Determination of Equivalent Acidity and Basicity of Fertilizers," *Analy. Ed., Ind. and Eng. Chem.,* 5: 229–234, 1933.

It is, of course, very difficult to determine the exact potential acidity of a given fertilizer. The approximate acidifying capacity of a few materials are cited below. The values are in terms of pounds $CaCO_3$ per 20 pounds N supplied by the fertilizer.

Ammonium sulfate	107	Ammonium nitrate	36
Ammo-phos	100	Cottonseed meal	29
Anhydrous ammonia	36	Castor pomace	18
Urea	36	High grade tankage	15

The basicity in the same terms for certain fertilizers is as below:

Nitrate of soda	36	Tobacco stems	86
Calcium cyanamid	57	Cocoa meal	12

ingredients, their composition, and the pounds of each in a ton of the mixture. Such a type of guarantee is given below (Table 18:6) for a 5–10–10 *neutral* fertilizer.

Table 18:6. An Open Formula Guarantee of a 5–10–10 (Non-acid Forming) Fertilizer

Pounds of Ingredients Per Ton	*Total* N *Lbs.*	*Available* P_2O_5 *Lbs.*	*Soluble* K_2O *Lbs.*
160 lbs. nitrogen solution	64		
150 lbs. sulfate of ammonia	30		
100 lbs. process tankage	6		
1000 lbs. superphosphate		200	
334 lbs. muriate of potash			200
256 lbs. dolomitic limestone			
2000 lbs. 5–10–10	100	200	200

Commercial fertilizers are sometimes grouped according to their nutrient *ratio*. For instance, a 5–10–10, a 6–12–12, a 10–20–20, and a 15–30–30 all have a 1–2–2 ratio. These fertilizers should give essentially the same results when suitably applied in equivalent amounts. Thus, 1,000 lbs. of 10–20–20 furnishes the same amounts of N, P_2O_5, and K_2O as does a ton of 5–10–10.

This grouping according to ratios is valuable when several analyses are offered and the comparative costs become the deciding factor as to which shall be purchased. Moreover, fertilizer recommendations are sometimes made on the basis of the ratio, the particular analysis being decided on later.

18:14. FERTILIZER INSPECTION AND CONTROL

So many opportunities are open for fraud, either as to availability or the actual quantities of ingredients present, that laws controlling the sale of fertilizers are necessary. These laws apply not only to the ready-mixed goods but to the separate carriers as well. Such regulations protect not only the public but also the reliable fertilizer companies, since goods of unknown value are kept off the market.

Certain provisions are more or less common to the various state fertilizer laws in this country. In general, there is a license fee or tonnage tax on all fertilizers selling for a certain price or over. In addition, the manufacturer must print the following data on the bag or on an authorized tag:

1. Number of net pounds of fertilizer to a package.
2. Name, brand, or trade-mark.
3. Chemical composition guaranteed.
4. Potential acidity in terms of lbs. of $CaCO_3$ per ton.
5. Name and address of manufacturer.

An example of how this information often appears on the fertilizer bag is shown in Figure 18:2.

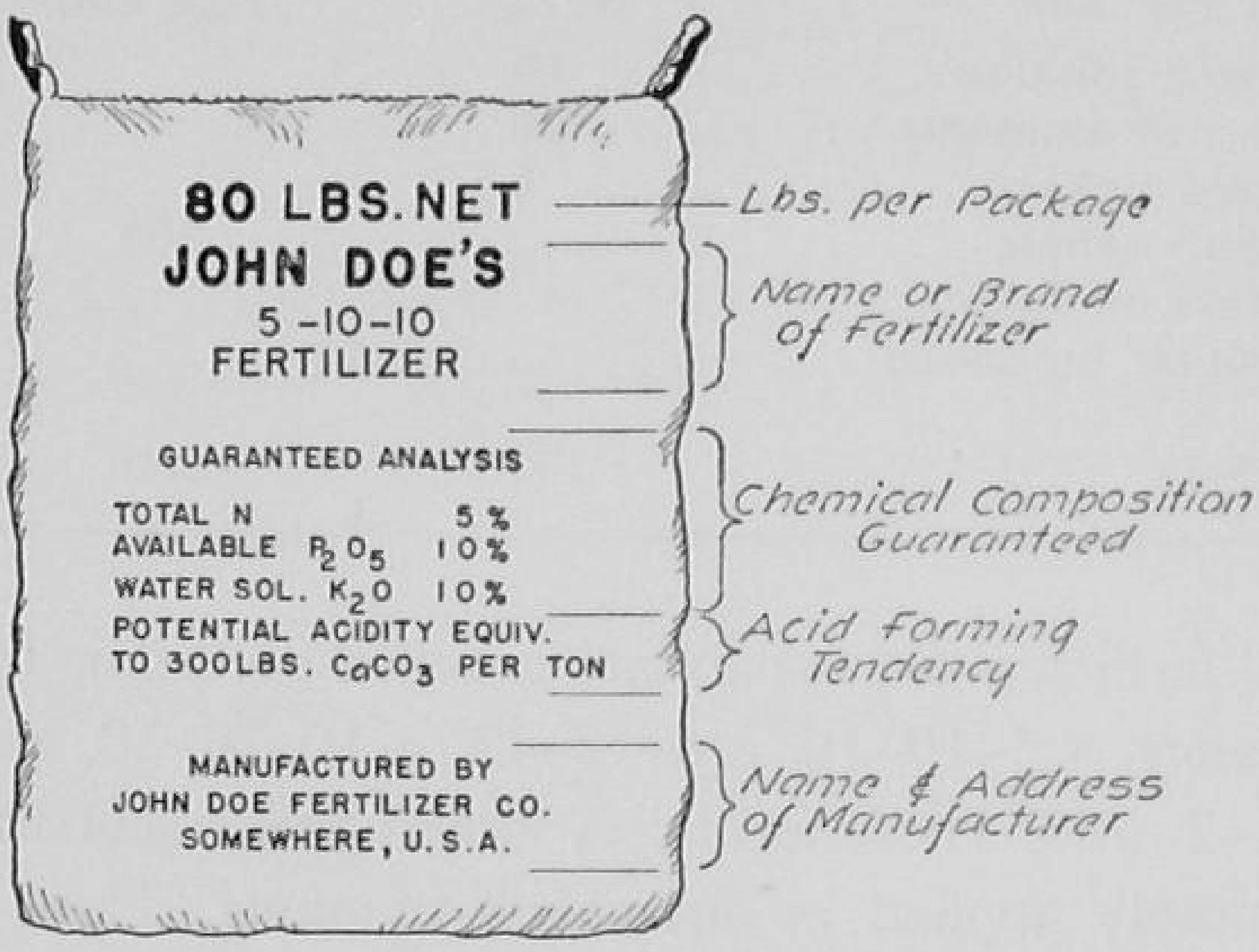


FIG. 18:2. *A fertilizer bag on which is printed the information commonly required by law in most states. Note the acid forming tendency of this particular fertilizer.*

For the enforcement of such laws the various states usually provide adequate machinery. The inspection and analyses may be in the hands of an agency such as the state department of agriculture, the agricultural experiment station, or the state chemist's office. In any case, inspectors are provided who take samples of the fertilizers on the market throughout the state. These samples are analyzed in order to ascertain whether the goods are up to the guarantee. The expense of the inspection and control of fertilizers is usually defrayed by a license fee or a tonnage tax.

If a fertilizer falls below the guarantee—allowing, of course, for any variation permitted by law—the manufacturer is subject to prosecution in the state courts.

A more effective check on fraudulent guarantees, however, is in publicity. The state law usually provides for the publication each year of a bulletin containing the "guaranteed" and "found" analyses of all brands inspected. This has proved to be very effective in preventing fraud. It protects not only the fertilizer user but also the manufacturer, as his guarantees

thus receive an official sanction. The "found" analysis of most fertilizers is generally up to or more often above the guarantee.

18:15. FERTILIZER ECONOMY

High *vs.* low analyses. Whether buying mixed fertilizers or the various separate carriers, such as nitrate of soda, sulfate of ammonia, and the like, it is always important to obtain high-analysis goods. Price data indicate that the higher the grade, especially of a mixed fertilizer, the greater is the amount of the various nutrients obtained for every dollar expended. This is a price rule well worth remembering. It holds because the overhead is about the same for every ton of fertilizer, regardless of the amount of nutrients that it contains. Concentration, therefore, reduces the overhead per unit of nutrient carried. This is shown graphically in Figure 18:3. Obviously, from the standpoint of economy, a 8–16–16 fertilizer furnishes more nutrients *per dollar* than a 4–8–8 or a 5–10–10.

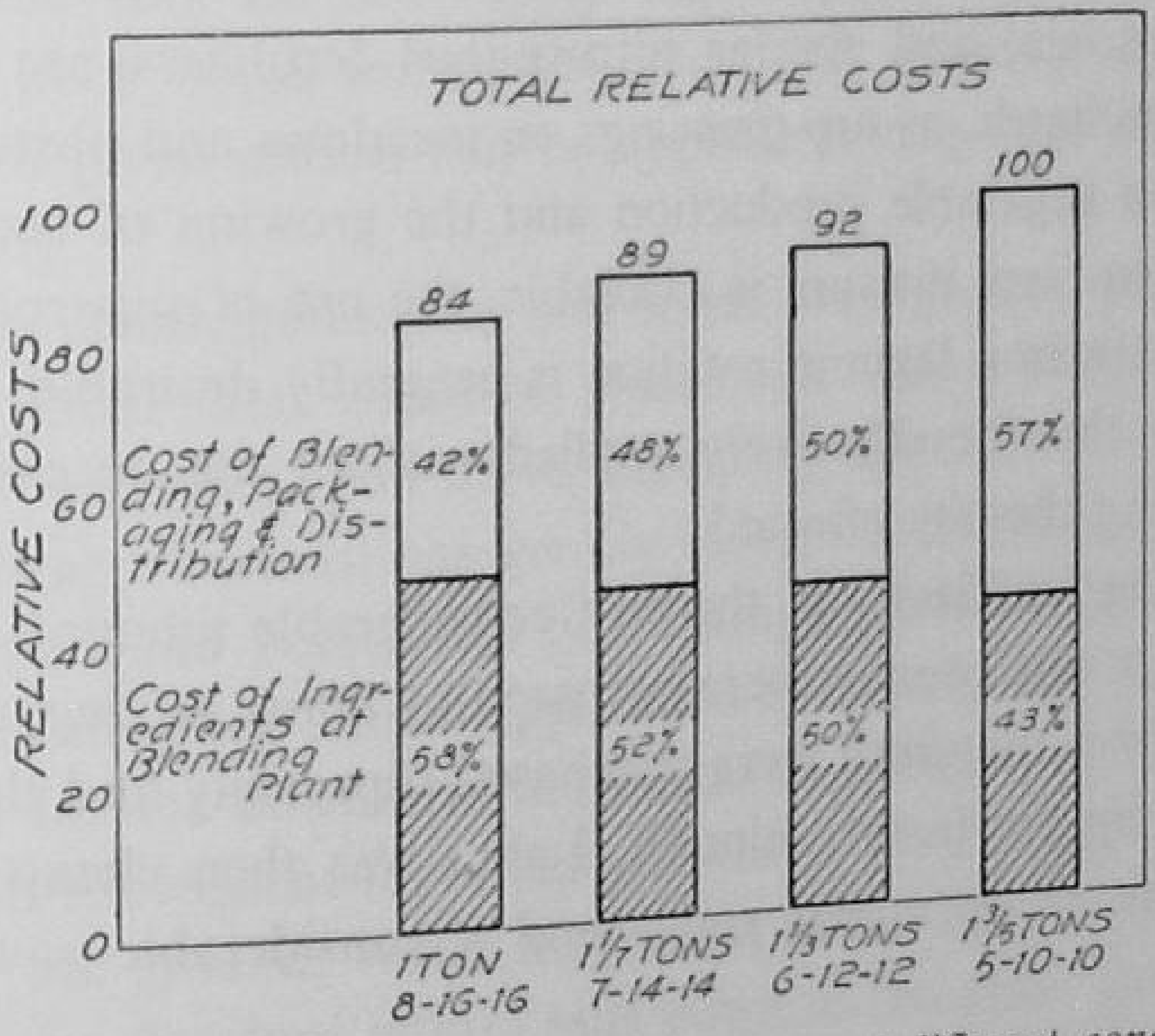


FIG. 18:3. *Relative farm costs of nutrients in fertilizer of different concentrations. Note that the same amount of* nutrients *is supplied by the indicated quantities of each fertilizer. These nutrients are furnished more cheaply by the higher analysis goods, mainly because of the lower handling costs.*

In the past certain disadvantages of high analysis fertilizers have somewhat hampered their increased usage. For example, the equipment used to place the fertilizer in the soil was too crude to satisfactorily distribute the smaller amounts of the more concentrated materials. Also, when improperly placed, the more concentrated goods often resulted in injury to young

seedlings. Modern fertilizer placement machinery, however, has largely overcome these difficulties. Hence, the savings which result from the use of higher analysis materials seem to far outweigh any associated disadvantages that may now exist.

Relative costs of N, P_2O_5 and K_2O. Another price factor to remember in purchasing fertilizers is the relative costs of nitrogen, phosphoric acid, and potash. Nitrogen has generally been more expensive than the other two constituents. This price differential has been somewhat reduced, however, due to the production of synthetic nitrogen carriers. Until recent years phosphoric acid was the least expensive of the three constituents. Since World War II, however, the cost of potash has been somewhat less than phosphoric acid. These facts should be kept in mind, especially when comparing the costs of fertilizers having different ratios.

Purchase of separate materials. In many instances a saving can be effected by purchasing the separate materials and applying them to the soil. Superphosphate is often applied alone for all sorts of crops. Nitrate of soda, sulfate of ammonia, and similar nitrogenous fertilizers are employed to advantage in orchards, as top-dressings on meadows and pastures, and as a side-dressing in vegetable production and the growing of such field crops as cotton. When farm manure is available, the use of superphosphate with lime and manure in a legume rotation is generally desirable. The separate fertilizers may thus be effectively applied without the necessity of mixing and some saving thereby effected.

Home mixing fertilizers. In the past considerable amounts of the mixed fertilizer used in this country were prepared by *home mixing,* that is, on the farm. The various materials were purchased separately and the compounding was done by the farmer himself. Labor was then cheap compared to the cost of the ready mixed goods and a considerable saving was thus possible.

At the present time, however, it is doubtful whether such savings are still possible by home mixing. In the first place, it is difficult to purchase the separate materials at reasonable prices, especially in small amounts. This is particularly discouraging to the individual farmer who does not need materials in amounts as large as a carload lot. On the other hand, if his operations are large enough to allow him to use fertilizer by the carload, he can often buy the manufactured mixed goods at a price considerably lower than that quoted for ton lots.

Another disadvantage of home mixing is the difficulty of obtaining the

most economic materials. For example, liquid ammonia, now the cheapest source of our most expensive major nutrient (nitrogen), cannot be used conveniently in home mixing because of the difficulties of handling. Also, proper conditioners are not too easily obtained and may be too expensive. And finally, it is often difficult to thoroughly mix the separate ingredients because of a lack of adequate equipment. These disadvantages discourage home mixing, especially when labor costs are high.

18:16. THE MOVEMENT OF FERTILIZER SALTS IN THE SOIL

To fully understand the reasons for some of the specific methods of applying fertilizers (see next section), the movement of fertilizer salts within the soil should be reviewed. As previously pointed out, phosphorus compounds tend to move but little, except in the more sandy soils. (See page 247.) Consequently, for maximum effectiveness this element should be placed in the zone of root development. Surface applications, unless worked into the soil, do not supply the deeper roots with phosphorus. Also, due to phosphorus immobility, the total quantity of this element necessary for a given season can be applied at one time without fear of loss by leaching.

On the other hand, potassium, and to an even greater extent, nitrogen, tend to move from their zones of placement. This movement is largely *vertical,* the salts moving up or down depending upon the direction of water movement. These translocations greatly influence the time and method of applying nitrogen and potassium. For example, it is often undesirable to supply nitrogen all in one annual application because of the leaching hazard. This tendency for the downward movement of nitrates is taken advantage of, however, in subsequent *top-dressings* where this fertilizer is applied on the surface of the ground. Water movement in the latter case is depended upon to carry the dissolved nitrate salts down to the plant roots.

The movement of nitrogen, and, to a lesser degree, potassium, must be considered in the *placement* of the fertilizer with respect to the seed. If the fertilizer salts are located in a band directly under the seeds, the upward movement of nitrates and some of the potassium salts by capillary water often results in injury to the stand. Rain immediately after planting followed by a long dry spell encourages such damage to seedlings. Placing the fertilizer immediately above the seed or on the soil surface also may result in injury especially to row crops. The possibility of such injuries should be kept in mind in reading the following section.

18:17. METHODS OF APPLYING SOLID FERTILIZERS[43]

Much emphasis is placed on the selection of the correct fertilizer ratio and on the adequate and economical amounts of the various fertilizers to be used. However the method of application is equally as important and must not be overlooked. A fertilizer should be placed in the soil in such a position that it will serve the plant to the best advantage. This involves not only different zones of placement but also the time of the year the fertilizer is to be applied. The methods of application will be discussed on the basis of the crops to be fertilized.

Row crops. Cultivated crops such as corn, cotton, and potatoes are usually fertilized in the *hill* or the *row,* part or all of the fertilizer being applied at the time of planting. If placed in the hill the fertilizer may be deposited slightly below and on one side, or better, on both sides of the seed. When applied to the row, the fertilizer usually is laid in as a narrow *band,* on one or both sides of the row, 2 or 3 inches away and a little below the seed level. (See Fig. 18:4.)

When the amount of fertilizer is large, it is often wise to broadcast part and thoroughly work it into the soil before the planting is done. In some cases the crop is side-dressed with an additional amount of fertilizer later in the season. This practice involves placing the fertilizer along the side of the row at a time most satisfactory to the crop. This requires experience and good judgment.

Vegetables. Vegetables are fertilized much the same as are other row crops. However, larger total amounts are usually applied and side-dressing is common, especially with a nitrogen fertilizer such as nitrate of soda. This is done after the crop is well started and is in addition to the regular fertilization. When the fertilizer is applied around the hill, as with such crops as melons, the treatment is called a *spot-application.*

Small grains. With small grains and similar crops the drill is equipped with a fertilizer distributor, the fertilizer entering the soil more or less in contact with the seed. As long as the amount of fertilizer applied does not exceed 300 or 400 pounds per acre, germination injury is not serious. Moreover, the sacrifice of some seedlings usually is not serious since more seeds than necessary commonly are planted. Besides, these crops tend to

[43] See "Methods of Applying Fertilizer," Recommendations of the National Joint Committee on Fertilizer Application, Published as Pamphlet No. 149 by the National Fertilizer Association, November, 1948.

stool abundantly. The final yield is consequently not very drastically affected by some fertilizer injury at time of germination.

Pastures and meadows. With meadows, pastures, and lawns, it is advisable to fertilize the soil well at the time of seeding. The fertilizer may be

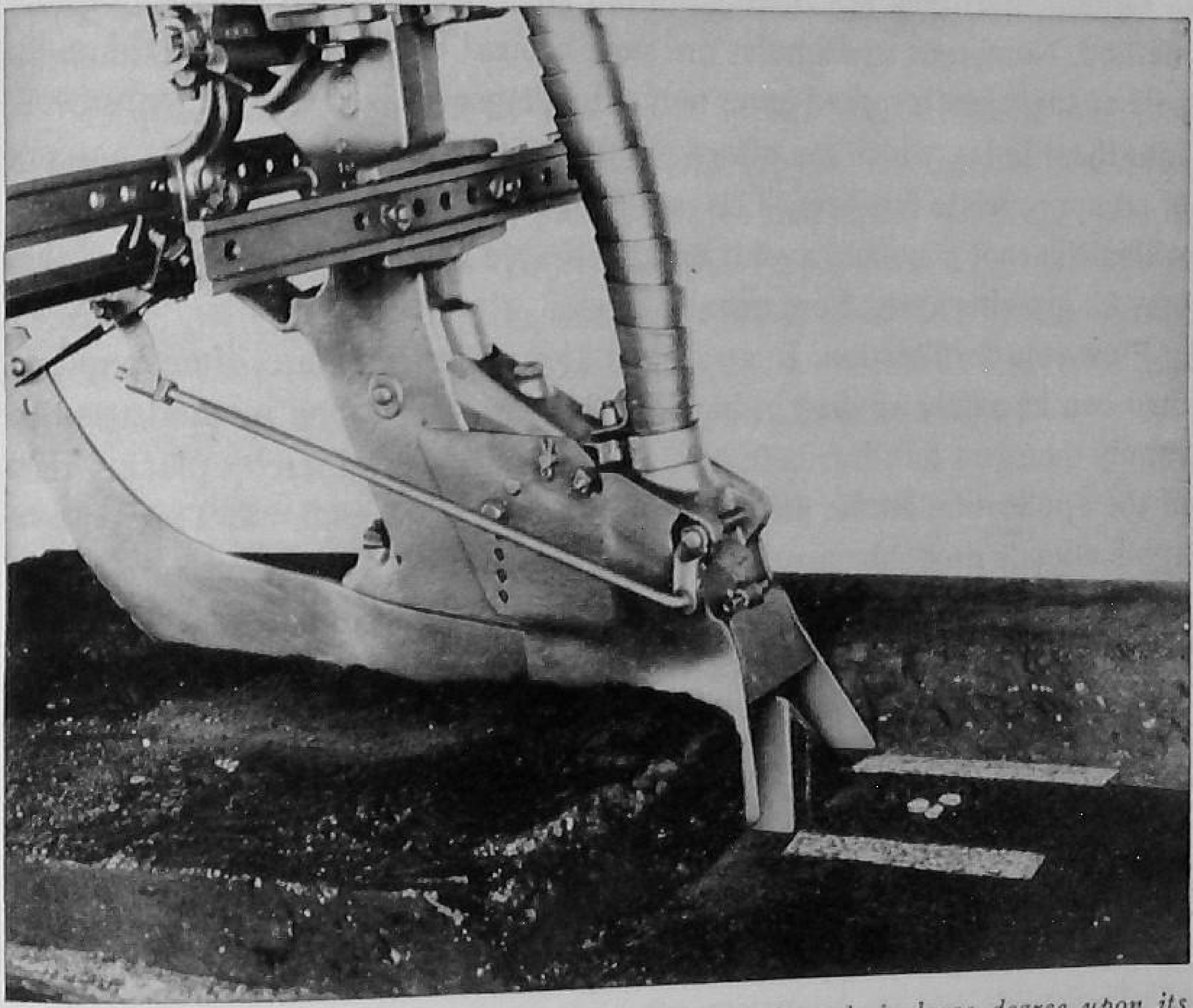


FIG. 18:4. *The effectiveness of a commercial fertilizer depends in large degree upon its placement in the soil. Machinery that will do this with satisfactory precision is now available. The illustration above shows the laying down of fertilizer bands at a satisfactory depth and at a suitable distance from the seed. One operation takes care of both planting and fertilizing. (Photo courtesy International Harvester Company.)*

applied with the seed, or better, broadcasted, and worked thoroughly into the soil as the seedbed is prepared. The latter method is preferable, especially if the fertilization is heavy. During succeeding years it may be necessary to top-dress such crops with a suitable fertilizer mixture. This requires care. The amount of fertilizer applied and the time of treatment should be so regulated as to avoid injury to the foliage and to the root crowns of the plants.

Trees. Orchard treees usually are treated individually, the fertilizer being applied around each tree within the spread of the branches but be-

ginning several feet from the trunk. The fertilizer is worked into the soil as much as possible. When the orchard cover-crop needs fertilization, it is treated separately, the fertilizer being drilled in at the time of seeding or broadcast later.

Ornamental trees are often fertilized by what is called the *perforation* method. Numerous small holes are sunk around each tree, within the outer half of the branch-spread zone and extending well into the upper subsoil. Into these holes, which are afterward filled up, is placed a suitable amount of an appropriate fertilizer. This method of application places the nutrients within the root zone and avoids an undesirable stimulation of the grass that may be growing around ornamental trees.

Plow-sole fertilization. Larger quantities of fertilizer are often required than can be safely applied in bands at planting time. One method used to supply the extra fertilizer is that of plowing under and thereby placing part of the application on the *plow sole* before the crop is planted. This type of application is probably most widely used as a supplementary measure rather than to replace the customary methods. Adverse weather conditions may seriously reduce the effectiveness of this procedure.

18:18. THE APPLICATION OF LIQUID FERTILIZERS [44]

The use of liquid materials as a means of fertilization is assuming considerable importance in certain areas of this country. Three primary methods of applying liquid fertilizers have been used: (a) direct application to the soil, (b) application in irrigation water, and (c) the spraying of plants with suitable fertilizer solutions.

Direct application to soil. The practice of making direct applications of liquid ammonia to soils is rapidly increasing in the Mississippi Delta and in regions in western United States. Special equipment is necessary which takes advantage of the pressure of the liquid ammonia to force the material into the soil. Little plant injury or wastage of ammonia occurs if the material is applied about four inches below the seed.[45] This method allows the direct utilization of the cheapest nitrogen source now available.

In irrigation water. In the West, particularly in California and Arizona, the application of liquid fertilizers in irrigation waters is gaining favor.

[44] For a review of this subject, see Mehring, A. L., "Fertilizers for Special Uses," a chapter in Amer. Soc. Agron. Monograph No. 3, 1952.

[45] For a discussion of this method, see Andrews, W. B., F. E. Edwards, and J. S. Hammons, *Ammonia as a Source of Nitrogen*. Miss. Agr. Exp. Sta. Bul. 451, 1943.

Liquid ammonia, phosphoric acid, and even complete fertilizers are allowed to dissolve in the irrigation stream. The nutrients are thus carried into the soil in solution. This requires no added application costs and allows the utilization of relatively inexpensive nitrogen carriers. Increased usage of these materials attest the growing popularity of the irrigation method of application.

Applied as spray on leaves. The direct application of urea to plants as a spray shows considerable promise.[46] This type of fertilization is unique. Nor does it involve any extra procedures or machinery since the urea is applied simultaneously with the insecticides. Apple trees seem to respond especially well as much of the urea nitrogen is absorbed by the leaves. Moreover, that which drips or is washed off is by no means lost for it falls on the soil from which it may later be absorbed by plants.

18:19. FACTORS INFLUENCING THE KIND AND AMOUNT OF FERTILIZERS TO APPLY

The agricultural value of a fertilizer is necessarily uncertain, since a material so easily subject to change is placed in contact with two wide variables, *the soil* and *the crop*. Soil conditions are constantly fluctuating, not only from year to year but progressively throughout the season. The kind and the amount of the fertilizer applied should, as nearly as possible, meet these changes.

Also, the soil and the added fertilizer *react* with each other often very vigorously both chemically and biologically. The reversion of phosphoric acid is an example of the first while the microbial decomposition of the organic ammoniates illustrates the latter. The result may be an increase or, more often, a decrease in the effectiveness of the fertilizer application. Due allowance should be made for these reactions when deciding on the kind and amount of fertilizer to apply.

Again there is *the weather* which has a tremendous effect on the soil, upon the crop, and upon the fertilizer applied. If there is either an excess or deficiency of moisture, full efficiency of the fertilizer cannot be expected. In fact, any factor which may tend to limit plant growth will necessarily reduce fertilizer efficiency, and consequently the crop response to fertilization. It is only when other factors are not limiting that the amounts of fertilizers can be estimated with any degree of certainty.

[46] Palmiter, D. H., *Soil and Foliage Applications of Nitrogen for Apple Scab Control*, N. Y. Agr. Exp. Sta., Farm Res., reprint 156, 1950.

In spite of the complexity of the situation, however, certain *guides* can be used in deciding the kind and amounts of fertilizers to be applied. The following are especially pertinent:

1. Kind of crop to be grown	economic value nutrient removal absorbing ability
2. Chemical condition of the soil in respect to	total nutrients available nutrients
3. Physical state of the soil, especially as to	moisture content aeration

The last of these factors in most cases has an indirect effect on fertilizer usage and has been discussed sufficiently elsewhere (pages 216 and 285). Consequently, only the first two will be considered in the following sections.

18:20. KIND OF CROP TO BE FERTILIZED

Crops of high economic value such as vegetables justify larger fertilizer expenditures per pound of response obtained. Consequently, for these crops complete fertilizers are used in rather large amounts. As much as 2,000 pounds or more of analyses such as a 4–8–12 or 5–10–10 are often recommended.

With crops having a low economic value per acre, much lower rates of fertilizer application are generally advisable. The extra yields obtained by applying large amounts of fertilizer are not usually sufficient, especially with such crops as pastures and meadows, to pay for the additional plant nutrients used.

It must always be remembered that the very highest yields obtainable under fertilizer stimulation are not always the ones that give the best return on the money invested. In other words, the law of diminishing returns is a factor in fertilizer practice regardless of the crop being grown. Therefore, the application of moderate amounts of fertilizer is to be urged for all soils until the maximum paying quantity that may be applied for any given crop is approximately ascertained.

If the nutrient removal by a given crop is high, fertilizer applications are usually increased to compensate for this loss. The extra fertilizer may be applied directly to the particular crop under consideration or to some preceding and more responsive crop in the rotation. It should not be implied that in all cases an attempt should be made to return nutrients in amounts

equivalent to those that have been removed. Advantage should be taken, particularly with respect to potash, of the nutrient supplying power of the soil. This source is usually insufficient, however, and extra fertilizer additions must be made. In fact, due to the vigorous reaction of phosphorus with soils, additions of this element in considerable excess of the amounts removed by crops and in other ways are usually economically sound.

Tremendous differences exist in the ability of plants to absorb nutrients from a given soil. For example, Lespedesa and peanuts, both of which are legumes, can readily absorb adequate potassium under much lower soil potash levels than can alfalfa or soybeans. Consequently, responses to additions of potassium usually are much greater with the latter two crops. Obviously, crop characteristics deserve very careful study.

18:21. CHEMICAL CONDITION OF THE SOIL—TOTAL VS. PARTIAL ANALYSES [47]

In adequately dealing with the problem of the kind and quantity of fertilizer to add to any particular soil, it is necessary to know, what nutrient element or elements are deficient. At first thought this might appear to be a very simple proposition. Chemistry has to its credit so many wonderful accomplishments that it would seem mere routine to analyze the soil for the various nutrient elements and immediately detect the constituents limiting crop growth.

As will appear later, however, this is asking rather too much unless the chemical data are extensively supplemented by information from other sources. No phase of soil science has received so much popular recognition as has chemical analysis; nor has any other *technical soil procedure* been so generally overrated in the minds of the general public. Nevertheless, certain of these tests (especially the "quick tests") are of considerable value when properly run and when interpreted by competent specialists who have information of a practical nature at their command.

Two general types of chemical analyses are commonly made in respect to the constituents present in soils—*total* and *partial*. In a *total analysis* the entire amount of any particular constituent present in the soil is determined, regardless of its form of combination and its availability. Such data

[47] Peech, M., *et al.*, *Methods of Soil Analysis for Soil Fertility Investigations*, Cir. 757, U. S. Dept. of Agriculture, 1947.

For plant tissue tests in respect to soil deficiencies, see Lynd, J. Q., *et al.*, "Nutrient Deficiencies Diagnosed with Foliar Analyses and Plant Tissue Tests," *Agron. Jour.*, 42: 402–407, 1950. A number of articles bearing on tissue testing are cited.

are of great value in studying soil formation and other phases of soil science. Ordinarily, however, they give little if any information on the availability of the essential elements to plants.[48] If this information is to be obtained, analyses suitable for measuring only the available portion of a given nutrient constituent must be employed. Such analyses are called *partial* since only a portion of the total quantity of a soil constituent is determined.

18:22. TESTS FOR AVAILABLE SOIL NUTRIENTS—QUICK TESTS[49]

Many procedures for the *partial analyses* of soils have been developed during the past half century. In general, these procedures attempt to extract from the soil amounts of certain fertility elements comparable to those removed by plants. The large number of extracting solutions which have been employed in trying to measure nutrient availability is mute testimony of the difficulties involved. The extraction solutions employed have varied from strong acids such as H_2SO_4 to weak solutions of CO_2 in water. Buffered salt solutions such as sodium or ammonium acetate are the extracting agents now most commonly used.

Quick tests—general consideration. The group of tests most extensively used for nutrient availability are the so-called *rapid* or *quick tests.*[50] As the name implies, the individual determinations are quickly made, a properly equipped laboratory being able to handle thousands of samples a year. Since

[48] For instance, many mineral soils are comparatively high in total potash (page 26), yet they very often respond profitably to potassium fertilization. A total analysis cannot be expected to detect with any accuracy this sort of situation.

[49] Although the determination of soil pH is easily and quickly made, it ordinarily is not included among these tests since it does not directly measure the availability of soil nutrients. Moreover, its interpretation is so unique and many sided as to put it in a class by itself. This test is discussed on page 410, with particular stress upon its practical interpretation.

[50] Truog, E., "The Determination of the Readily Available Phosphorus in Soils," *Jour. Amer. Soc. Agron.,* 22: 874–882, 1930.

Hance, Francis E., *Soil and Plant Material Analyses by Rapid Chemical Methods,* Bulletins 50 and 51, Hawaiian Sugar Planters' Assoc., 1936 and 1937.

Spurway, C. A., *Soil Testing—A Practical System of Soil Fertility Diagnosis,* Technical Bulletin 132, 2nd rev., Mich. Agr. Exp. Sta., 1938.

Bray, R. H., *Rapid Tests for Measuring and Differentiating Between the Adsorbed and Acid-Soluble Forms of Phosphate in Soils,* Mimeograph Pamphlet A. G. 1028, Ill. Agr. Exp. Sta., 1942 and *Directions for Modified Tests for Replaceable Potassium in Soils,* Mimeograph Pamphlet A. G. 1033, Ill. Agr. Exp. Sta., 1942.

Peech, M., and L. English, "Rapid Microchemical Soil Tests," *Soil Sci.,* 57: 167–195, 1944.

Lunt, H. A., *et al., The Morgan Soil Testing System,* Bul. 541, Conn. Agr. Exp. Sta., 1950.

these tests are the only ones having practical possibilities for widespread usage, their limitations as well as their merits will be critically reviewed.

A weak extracting solution such as buffered sodium acetate is generally employed in rapid tests and only a few minutes are allowed for the extraction. Most of the nutrients removed are those rather loosely held by the colloidal complex. The test for a given constituent may be reported either in general terms, such as *low, medium,* or *high,* or more specifically, in pounds per acre. The constituents most commonly tested for are phosphorus, potassium, calcium, and magnesium while aluminum, iron, and manganese are frequently included.

Limitations of quick tests. With this general description as a background, we are in a position to consider the specific *limitations* and *merits* of rapid tests. Perhaps the first limitation is the difficulty of properly *sampling soils* in the *field*. Generally only a very small sample is taken, perhaps a pint or so from an area of land often several acres in size. The chances of error, especially if only a few borings are made, are quite high. In general, at least 15 to 20 borings are suggested for each sample in order to increase the probability that a representative portion of the soil has been obtained.

A second limitation of these tests is the fact that their chemical procedures are somewhat *arbitrary*. It is essentially impossible to extract from a soil sample in a few minutes the amount of a nutrient, or even a constant proportion thereof, that a plant will absorb from that soil in the field during the entire growing season. To make matters worse, serious *technical difficulties* are sometimes encountered in accurately determining the amounts of the several nutrients even after they are extracted. This emphasizes the importance of good scientific equipment as well as technical knowledge and skill in making rapid tests.

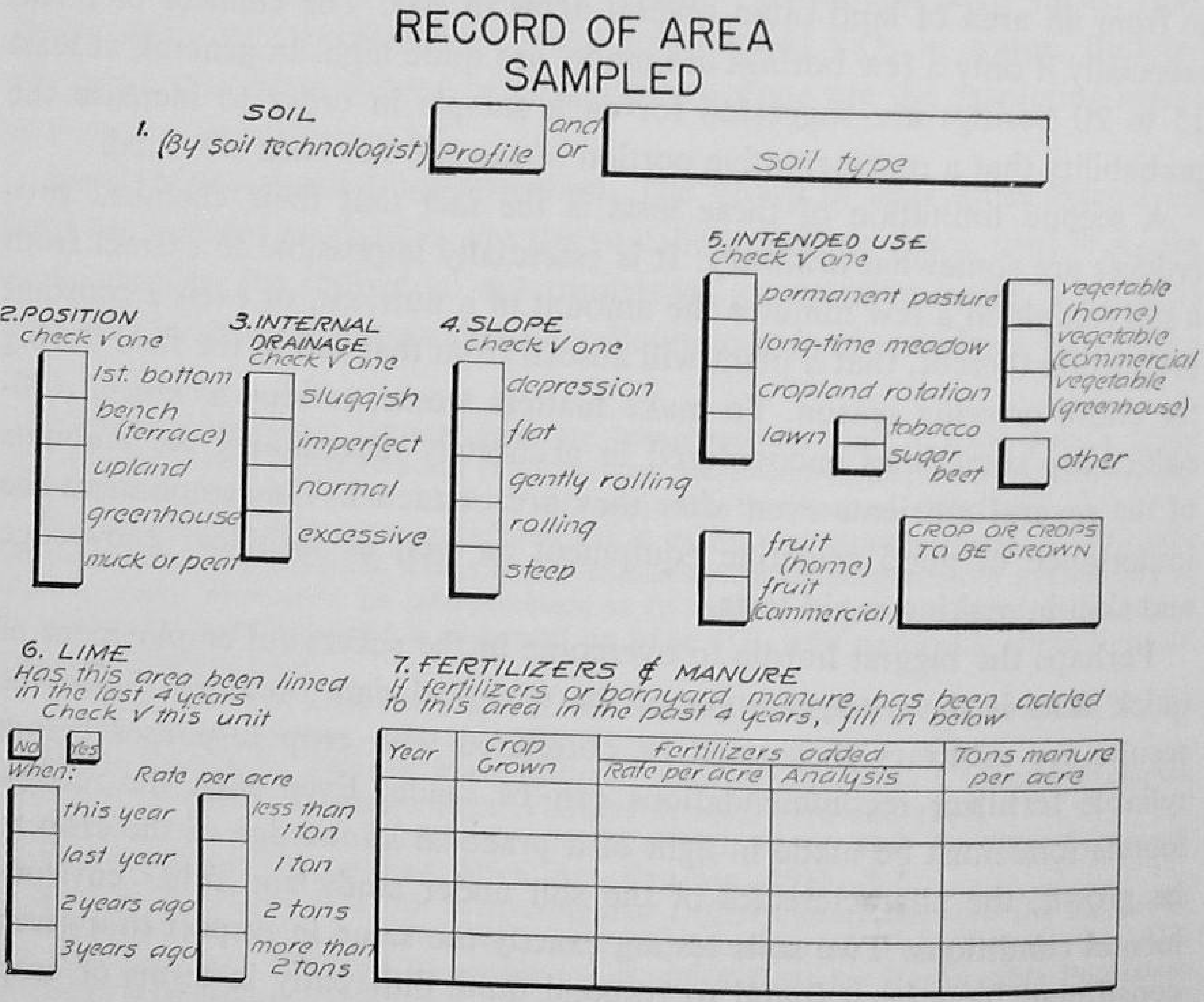
Perhaps the biggest hurdle to overcome in the successful employment of quick tests is the *interpretation* of the chemical data obtained. Since the results are arbitrary they must be correlated with crop responses before reliable fertilizer recommendations can be made. Even then the recommendations must be made in light of a practical knowledge of the crop to be grown, the characteristics of the soil under study and other environmental conditions. Two soils testing exactly the same in respect to a given constituent have been found to respond quite differently in terms of crop yields to identical fertilizer treatments in the field.

Trained personnel should make and interpret tests. Obviously, it is unwise to place any particular confidence in fertilizer recommendations when

the tests are made and interpreted by an amateur. Not only might the novice make inaccurate determinations but he is sure to lack the knowledge and judgment necessary for a rational interpretation in terms of fertilizer needs.

Obviously the interpretation of quick test data is best accomplished by experienced and technically trained men, who fully understand the scientific principles underlying the common field procedures. Although the rapid tests themselves are made by specially trained analysts and not usually by the soil and crop specialists, the latter fully understand the interpretation and limitations of the chemical data furnished them.

As already suggested, it is essential that a person have considerable related information in order to make the proper use of quick test data. Examples of supplementary data desirable are shown by the sample information sheet in Figure 18:5. This supplementary information may be as helpful as the actual test results in making fertilizer recommendations.



RECORD OF AREA SAMPLED

1. SOIL (By soil technologist) Profile and or Soil type

2. POSITION check √ one
1st. bottom
bench (terrace)
upland
greenhouse
muck or peat

3. INTERNAL DRAINAGE Check √ one
sluggish
imperfect
normal
excessive

4. SLOPE check √ one
depression
flat
gently rolling
rolling
steep

5. INTENDED USE Check √ one
permanent pasture
long-time meadow
cropland rotation
lawn
tobacco
sugar beet
vegetable (home)
vegetable (commercial)
vegetable (greenhouse)
other
fruit (home)
fruit (commercial)
CROP OR CROPS TO BE GROWN

6. LIME
Has this area been limed in the last 4 years
Check √ this unit
No Yes
When:
this year
last year
2 years ago
3 years ago
Rate per acre
less than 1 ton
1 ton
2 tons
more than 2 tons

7. FERTILIZERS & MANURE
If fertilizers or barnyard manure has been added to this area in the past 4 years, fill in below

Year	Crop Grown	Fertilizers added: Rate per acre	Fertilizers added: Analysis	Tons manure per acre

FIG. 18:5. *A satisfactory interpretation of a quick test analysis of a soil can not be made without certain pertinent field data. The record sheet above suggests the items that are most helpful to the expert in making a fertility recommendation. (Modified from a form in use by the Ohio Agr. Exp. Sta.)*

Merits of rapid tests. It must not be inferred from the preceding discussion that the limitations of rapid tests outweigh their advantages. In fact, when the precautions already cited are observed, rapid tests are an invaluable tool in making fertilizer recommendations. Moreover, these tests will become of even greater importance in so far as they are correlated with the results of field fertilizer experiments. Such field trials undoubtedly will be expanded to keep pace with the increasing use of the rapid tests.

18:23. THE BROADER ASPECTS OF FERTILIZER PRACTICE

It is obvious that fertilizer practice involves many intricate details regarding soils, crops, and fertilizers. In fact, the interrelations of these three are so complicated and far reaching that a practical grasp of the situation requires years of experience. The unavoidable lack of exactness in fertilizer decisions should ever be kept in mind.

Leaving the details and viewing the situation in a broad way, it seems to be well established that any fertilizer scheme should provide phosphoric acid and potash in amounts sufficient to balance the nitrogen, since this element is so active and subject to such ready loss from the soil. A plan that calls for an abundance of minerals is a sound one if it does not unduly waste nutrients by fixation or by leaching. Such a plan, coupled with a heavy fertilization of the money crop, does not, however, constitute all that is deemed fundamental in a rational system of soil fertilization.

Not only must the soil, the crop, and the fertilizer receive careful study, but the crop rotation employed and its management should be considered in addition. Obviously, also the fertilizer applications must be correlated with the use of farm manure, crop residues, green manure, trace elements, and lime. Moreover, the residues of previous fertilizer additions must not be forgotten. In short, fertilizer practice is only a phase, but a very important one, of the fertility management of soils.

CHAPTER

19

Farm Manure and Green Manure

FARM MANURE is one of the most important agricultural by-products. By its utilization part of the unused portion of the crop may enter the soil, there to exert an influence far greater than its nutrient content would lead one to expect. The world has already entered an era in which the prevention of agricultural waste is becoming necessary. Therefore, up-to-date farm management demands a more careful handling, as well as a wiser utilization of the manure produced on the farm.

19:1. THE CHEMICAL COMPOSITION OF FARM MANURE [1]

The term *farm manure* is employed in reference to the refuse from all animals of the farm, although as a general rule the bulk of the manure which ultimately finds its way back to the land is produced by cattle. This is supplemented to a greater or less extent by manure from horses, hogs, sheep, and poultry.

Farm manure consists of two original components, the *solid* and the *liquid,* in about the ratio of 3 to 1. On the average, a little more than *one-half the nitrogen,* almost *all of the phosphoric acid,* and about *two-fifths of the potash* are found in the solid manure. (See Fig. 19:1.) Never-

[1] For analyses of farm manure, see:
Van Slyke, L. L., *Fertilizers and Crop Production,* Orange Judd Publishing Company, Inc., New York, 1932, pp. 216–226.
Thorne, C. E., *Farm Manures,* Orange Judd Publishing Company, Inc., New York, 1941, pp. 89–93.
Gustafson, A. F., "Farm Manure—Its Production, Management and Use," Extension Bul. 642, Cornell Univ. Agr. Exp. Sta., 1944.
Gustafson, A. F., "Poultry Manures," War Emergency Bul. 117, Cornell Univ. Agr. Exp. Sta., 1944.

theless, this apparent advantage of the solid manure is offset by the ready availability of the constituents carried by the urine, giving the latter about an equal agricultural value with the solid excrement. Such figures are suggestive of the care that should be taken of the liquid manure.

While extended data are available as to the chemical composition of the liquid and solid portions of the excreta from the various farm animals,[2] it is extremely difficult to quote reliable average figures on mixed farm manure as it ordinarily is applied to the land. This is because a number of variable factors enter in which may radically change the amounts and proportions of nitrogen, phosphoric acid, and potash present. The more important of these factors are: (1) kind of animal, (2) age, condition, and individuality of animals, (3) food consumed, (4) litter used, and (5) the handling and storage which the manure receives before it is spread on the land.

In spite of the marked variability of farm manure, representative composition figures will be ventured. For purposes of calculation and discus-

[2] The composition of fresh animal-excrement [a]

	Excrement, percentage	Percentage of			
		H_2O	N	P_2O_5	K_2O
Horse	Solid, 80	75	0.55	0.30	0.40
	Urine, 20	90	1.35	Trace	1.25
	Whole manure	78	0.70	0.25	0.55
Cow	Solid, 70	85	0.40	0.20	0.10
	Urine, 30	92	1.00	Trace	1.35
	Whole manure	86	0.60	0.15	0.45
Sheep	Solid, 67	60	0.75	0.50	0.45
	Urine, 33	85	1.35	0.05	2.10
	Whole manure	68	0.95	0.35	1.00
Swine	Solid, 60	80	0.55	0.50	0.40
	Urine, 40	97	0.40	0.10	0.45
	Whole manure	87	0.50	0.35	0.40
Hens	Whole manure	55	1.00	0.80	0.40

[a] VanSlyke, L. L., *Fertilizers and Crop Production*, Orange Judd Publishing Company, Inc., New York, 1932, p. 218.

[2] Commercial Pulverized Animal Manures [b]

Fertilizer	Percentage of		
	N	P_2O_5	K_2O
Sheep	2.50	1.50	1.50
Goat	1.35	1.40	3.60
Poultry	4.50	3.20	1.35

[b] *Ibid.*, p. 171.

sion, average farm manure ready for field application will be considered as containing *0.5 per cent of nitrogen, 0.25 per cent of phosphoric acid,*

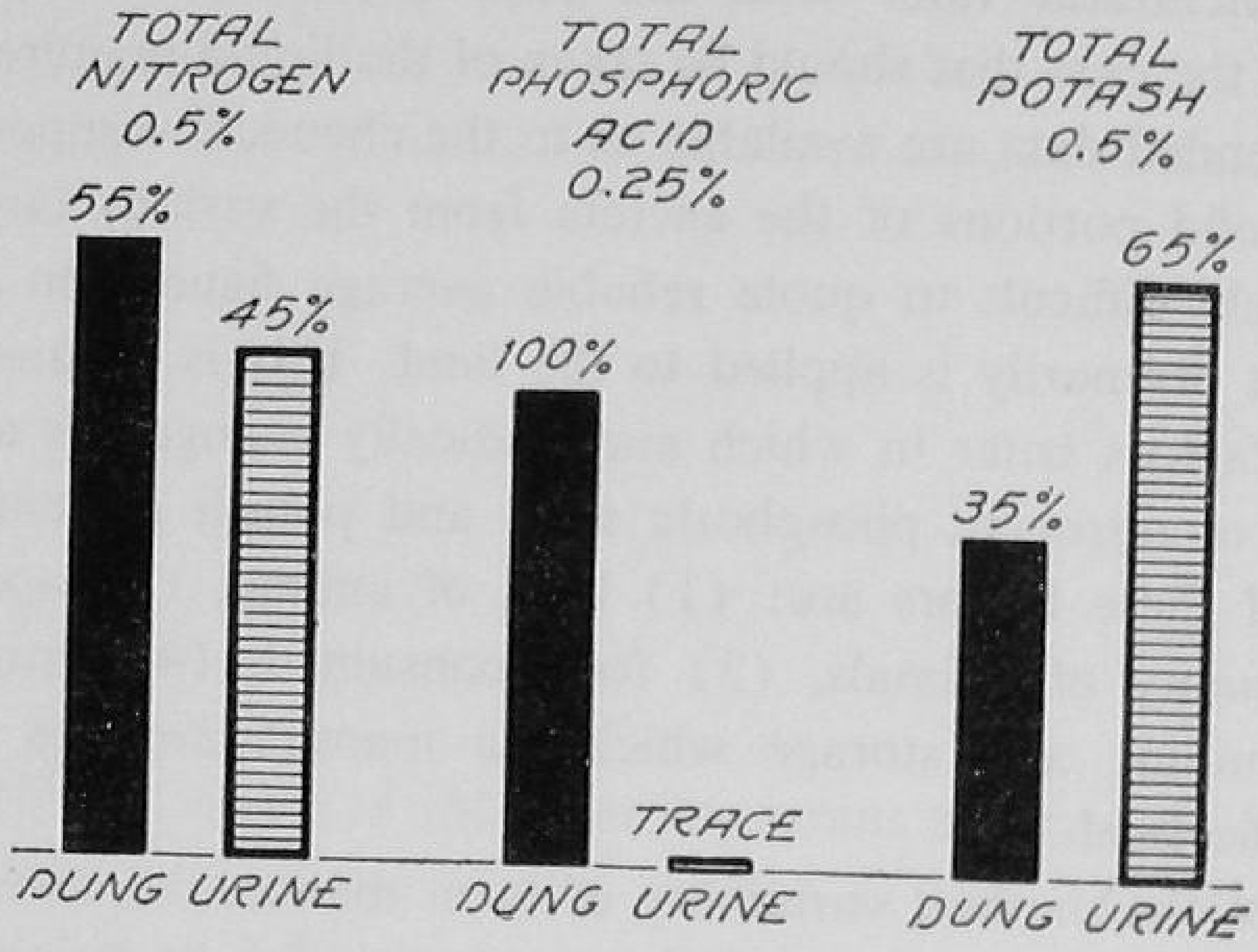


FIG. 19:1. *Diagram showing the distribution of nitrogen, phosphoric acid, and potash between the solid and liquid portions of average farm manure.*

and *0.5 per cent of potash.* The tentative nature of such figures, however, must always be kept in mind. Besides nitrogen, phosphorus, and potassium, farm manure contains calcium, magnesium, sulfur, and probably all of the trace elements. The latter are in some cases extremely important in the maintenance of a balanced nutrient condition in soils so treated.

19:2. OUTSTANDING CHARACTERISTICS OF FARM MANURE [3]

As a farm manure is essentially a fertilizer, it is logical to contrast it with the ready-mixed commercial fertilizers on the market. In such a

[3] Data as to the amounts of manure likely to be produced by the different classes of farm animals are often useful in fertility calculations.

Tons of Manure Produced Annually by Farm Animals per 1,000 Pounds Live Weight [a]

Animal	*Weight of Excrement*	*Weight of Bedding*	*Total Weight*
Horse	9.00	3.0	12.00
Cow	13.50	1.5	15.00
Pig	15.25	3.0	18.25
Sheep	6.25	3.5	9.75
Steer	7.50	1.5	9.00
Hen	4.75	—	4.75

[a] VanSlyke, L. L., *Fertilizers and Crop Production,* Orange Judd Publishing Company, Inc., New York, 1932, p. 287.

comparison, six characteristics are outstanding: (1) the moist condition of manure, (2) its variability, (3) its low analysis, (4) its unbalanced nutrient condition, (5) the residual influence exerted by farm manure, and (6) its rapid fermentative processes.

Moisture and variability. Of the above characteristics the first two may be disposed of quickly. The variability of farm manure has already been sufficiently emphasized since it is a condition ordinarily to be expected. As to the moisture, whether in fresh or well-rotted manure, the amount may vary from 50 to 80 per cent depending on conditions.

Low analysis. Since representative farm manure is considered to contain 0.5 per cent of nitrogen, 0.25 per cent of phosphoric acid, and 0.5 per cent of potash, a ton of this material supplies only 10, 5, and 10 pounds of total nitrogen, phosphoric acid, and potash respectively. It is without doubt a low-analysis material when compared to the commercial fertilizers commonly on the market, such as a 5–10–10 for instance, which supplies 100, 200, and 200 pounds per ton respectively of these three constituents.

It must not be assumed, however, that the amounts of the three fertilizer elements added to an acre of land in an ordinary application of farm manure are correspondingly small. Because of the large acre applications of this fertilizer (10, 15, or even 20 tons an acre) the quantities of the nutrient elements added are comparatively large. For example, 10 tons of representative farm manure will supply in total about 100 pounds of nitrogen, 50 pounds of phosphoric acid, and 100 pounds of potash. This is equal in terms of total nutrients to 625 pounds of nitrate of soda (16 per cent), 312 pounds of superphosphate (16 per cent), and 166 pounds of potassium chloride (60 per cent).

In such a comparison, however, it is well to remember that only a part of the nutrient constituents of farm manure is readily available. In general, only about *one-half of the nitrogen, one-sixth of the phosphoric acid,* and a little more than *one-half of the potash* are readily available (during the first season) to plants. On the basis of readily available nutrients 1 ton of average farm manure supplies approximately 5 pounds of N, 1 pound of P_2O_5, and 5 pounds of K_2O.

Nutrients unbalanced. The phosphoric acid of most mineral soils is not only low but rather unavailable. Moreover, the phosphorus added in fertilizers is adsorbed rather strongly by the soil complex and is likely, in part at least, to become inactive. As a consequence, it seems necessary for a

complete fertilizer to carry as much or even more phosphoric acid than nitrogen or even potash. The ratio of a ready-mixed complete commercial fertilizer in respect to these three constituents ($N—P_2O_5—K_2O$) ordinarily is seldom less than 1–1–1 or 1–2–1, while in some cases the ratio is as high as 1–3–1.

Farm manure with an availability ratio of 5–1–5 is obviously too low in phosphoric acid to be fully effective and is considered as unbalanced for that reason. It is often advisable, especially when the farm manure is used for cereal crops, to correct this condition by reinforcing it with suitable amounts of superphosphate or some other phosphatic fertilizer. (See page 543.)

Residual effects. The length of time through which the effects of an application of farm manure may be detected in crop growth is surprising. Hall [4] cites data from the Rothamsted experiments in which the effects of eight yearly acre applications of 14 tons each were apparent forty years after the last treatment. This, of course, is an extreme case. Ordinarily, profitable increases may be obtained from manure only for three or four years after the treatment.

The sixth outstanding characteristic of farm manure, its fermentative and decay activities, will be considered in the following section.

19:3. THE FERMENTATION OF MANURE [5]

In the process of digestion, the food of animals becomes more or less decomposed. This condition comes about partly because of the digestive processes themselves and partly from the concurrent bacterial action that takes place. Consequently, the fresh excrement, as it comes from the stable, consists of decayed or partially decayed plant materials. This is more or less intimately mixed with litter and the whole mass is moistened with the liquid excrement carrying considerable quantities of soluble compounds of nitrogen, potassium, and other nutrients. Moreover, the whole mass is teeming with bacteria and other organisms.

Aerobic fermentation. When manure is first produced, it is usually

[4] Hall, A. D., *Fertilizers and Manures*, E. P. Dutton and Company, Inc., New York, 1928, p. 234.

[5] For discussions concerning the decomposition of manure, see Russell, E. J., and E. H. Richards, "The Changes Taking Place during the Storage of Farm Manure," *Jour. Agr. Sci.*, 8; Part 4: 495–563, 1917; and Waksman, S. A., *Principles of Soil Microbiology*, The Williams and Wilkins Company, Baltimore, 1932, Chap. 25.

somewhat loose, especially if considerable litter is present. The first microbial changes are, therefore, likely to be largely aerobic in nature. These transformations usually are rapid and are accompanied by considerable heat. This is commonly the case with horse manure particularly.

The simple nitrogenous compounds are influenced first, although the more complicated constituents are by no means unaffected. Carbon dioxide is given off in large quantities. The urea of the urine is readily influenced by aerobic activities and quickly undergoes hydrolysis. The ammonium carbonate which results is unstable and promptly produces ammonia. The odor of this gas in horse stables gives evidence of such a change.

$$CO(NH_2)_2 + 2\ H_2O \longrightarrow (NH_4)_2CO_3$$

$$(NH_4)_2CO_3 \longrightarrow 2\ NH_3\uparrow + CO_2\uparrow + H_2O$$

If conditions are favorable for nitrification, and such is likely to be the case, nitrates may appear in abundance. Since such compounds of nitrogen are very soluble and subject to but little adsorption, serious leaching losses may occur.

Moreover, the nitrites, instead of being quickly oxidized to the nitrate form, may liberate elemental nitrogen by reacting with other nitrogen compounds such as amides, amines, and ammonium salts (page 456). A twofold loss of nitrogen is likely to result. This loss of nitrogen due to the chemical activity of the nitrites may be much more important in the manure pile than has been suspected. Hence, in the earlier and better aerated decomposition stages, farm manure may be depleted of its nitrogen in three forms—ammoniacal, nitrate, and elemental.

Anaerobic decay. As the manure becomes compacted, especially if it is moist and in a pile, the gaseous oxygen is gradually used up while carbon dioxide is released. The decay now changes from aerobic to anaerobic, it becomes slower, and the temperature tends to fall. New organisms may now function, although many of those active under aerobic conditions probably continue to be effective. The products become changed to a considerable degree. Carbon dioxide, of course, is still evolved in large amounts, but instead of ammonia being formed, the nitrogenous matter is converted, at least in part, into the usual putrefactive products. And since conditions are ideal for biochemical reduction, amines, amides, ammonium, nitrites, and nitrates are readily affected in this way. As a result, considerable amounts of gaseous nitrogen are evolved.

Reduction in bulk. Because of the great loss of carbon dioxide and water during these decay processes, there is a considerable reduction in the bulk of the manure. Fresh excrement readily loses from 20 to 40 per cent in bulk by partial rotting and perhaps 50 per cent as it becomes more thoroughly decomposed. It is often argued that, if the manure is properly stored, this rapid loss of carbon dioxide and water should raise the percentage amounts of the fertilizer elements present. This may be true for potash and phosphoric acid. But in practice the losses in handling due to leaching and fermentation sometimes are so pronounced as to place well-rotted manure at a disadvantage as far as its total supply of plant nutrients is concerned. This is especially likely to be the case in respect to nitrogen which is subject to losses by both volatilization and leaching.

Well decayed *vs.* fresh manure. In many cases, however, well-rotted manure [6] is more desirable than the fresh material. This is especially true if the fresh manure is strawy. The addition of straw to a soil may widen its carbon-nitrogen ratio and reduce as well as prevent the formation of nitrate nitrogen (page 166). Strawy manure apparently tends to produce the same effect and a crop immediately following its application, may show nitrogen starvation. Under such conditions the well-decayed product is more desirable. When manure is used as a top-dressing, as is sometimes the case with fall wheat and other crops, well-rotted material should always be applied if possible.

In trucking and vegetable gardening, well-decomposed manure is generally preferred. Such is also the case with home gardens, flower beds, lawns, and greenhouses. *Composting,*[7] which is largely a biological process,

[6] A change of a biological nature which takes place if the manure dries out too much is *fire-fanging.* Many people consider this to be due to actual combustion, as the manure is very light in weight and has every appearance of being burned. This condition, however, is produced by fungi and the dry and dusty appearance of the manure is due to the mycelia, which penetrate in all directions and use up the valuable constituents. Manure thus affected is of little value either as a fertilizer or as a soil amendment.

[7] A compost is commonly made of alternate layers of manure and the vegetable matter that is to be decayed. Layers of sod or of soil high in organic matter may also be introduced to advantage. The manure supplies especially active decay organisms which, in the presence of nitrogen, cause a rapid and effective humification. The foundation of such a compost is usually soil, and the pile is preferably capped with earth.

The mass should be kept moist in order to reduce the loss of ammonia and elemental nitrogen and to encourage vigorous bacterial action. Superphosphate is often added to balance up the mixture and make it more effective. A nitrogen fertilizer may also be employed with profit as well as ground limestone.

is often resorted to, especially in the latter cases, farm manure being used in building up the compost pile. Because of its high organic content and the influence of its nitrogen and microorganisms, manure is especially valuable for such purposes.

19:4. ARTIFICAL FARM MANURE

A product spoken of as *artificial farm manure* was devised in England during the First World War by decomposition of straw and other materials under more or less controlled conditions.[8] The method used in the United States is similar.[9] The straw as it is stacked, or packed into containers, is treated, layer by layer, with a mixture of fertilizer salts of which nitrate of soda or sulfate of ammonia is prominent. Ground limestone and superphosphate are also added. Other salts are sometimes used in addition. The straw is kept thoroughly moist and compacted, and if the weather is warm, decay begins almost immediately.

The added fertilizers greatly hasten the decomposition of the wet straw and within eight months or a year the artificial manure is ready for use. The product closely resembles ordinary farm manure in appearance but is somewhat better balanced in chemical composition because of the fertilizers added. Field tests indicate that such material usually is equal to farm manure as a fertilizer.[10]

A number of different formulae have been suggested for treating the straw. Perhaps the following is as good as any. It calls for 160 pounds of a fertilizer mixture for each ton of dry straw as follows: 70 pounds of sulfate of ammonia, 50 of ordinary superphosphate, 30 of limestone, and 5 pounds each of magnesium sulfate and common salt.

In those parts of the United States and other countries where grain farming is practiced and large amounts of straw are available, the scheme could be of value in reducing such material to a form whereby it may be applied to the soil without radically widening the carbon-nitrogen ratio.

[8] Hutchinson, H. B., and E. H. Richards, "Artificial Farm Manure," *Jour. Min. Agr., Great Britain,* 28: 398–411, 1921.

[9] Halverson, W. V., and E. F. Torgerson, "Production of Artificial Farmyard Manure by Fermenting Straw," *Jour. Amer. Soc. Agron.,* 19: 577–584, 1927.

Albrecht, W. A., and E. M. Poirot, "Farm Trials with Artificial Manure," *Jour. Amer. Soc. Agron.,* 20: 123–132, 1928.

Turk, L. M., *Synthetic Manure Production in Michigan,* Circular Bulletin 157, Mich. Agr. Exp. Sta., 1936.

[10] Brown, P. E., and F. B. Smith, "The Production of Artificial Manure from Oats Straw under Control Condition," *Jour. Amer. Soc. Agron.,* 21: 310–322, 1929.

The undesirable effects of plowing under the fresh straw could thus be avoided. However, the scheme is not commonly employed even in grain farming and with the increasing popularity of trash-mulches (see page 229) the extensive production of artificial farm manure is not to be expected.

The feasibility of producing artificial manure for the growing of vegetables or for use in dairy sections is yet to be demonstrated. In the former case the source of organic residues would be a difficult problem. In the latter case much of the straw would be used as bedding.

19:5. NUTRIENT LOSSES DURING MANURIAL PRODUCTION

A certain amount of every crop is lost before it is consumed by animals. Such loss is usually small on most farms, especially when compared to the nutrients retained by the livestock. Attention is therefore particularly directed toward those losses sustained by the food as it undergoes normal digestion, and is about to be voided.

As might be expected, the data [11] bearing on this phase is variable, since so much depends on the age, conditions, individuality, and class of animal, and the character of the food. As a generalization and for purposes of calculation, it may be considered that *three-fourths of the nitrogen, four-fifths of the phosphorus, nine-tenths of the potash,* and *one-half of the organic matter* are recovered in the voided excrement. This means losses of about 25, 20, 10, and 50 per cent respectively for these constituents. (See Fig. 19:2.)

19:6. LOSSES DURING THE HANDLING AND STORAGE OF FARM MANURE

Since approximately one-half of the nitrogen and three-fifths of the potash of average farm manure are in a soluble condition, the possibility of loss by leaching is usually great, even though the manure is not exposed to especially heavy rainfall. In addition, decomposition, both of an aerobic and anaerobic nature, will cause a rapid waste of nitrogen in the ammonium, nitrate, and elemental forms. Packing and moistening the

[11] Experimental results are reported in the following publications:
Frear, W., *Losses of Manure,* Bulletin 63, Penn. Agr. Exp. Sta., 1903.
Thorne, C. E., *Maintenance of Fertility,* Bulletin 183, Ohio Agr. Exp. Sta., 200–202, 1907.
Wood, T. B., "Losses in Making and Storing Farmyard Manure," *Jour. Agr. Sci.,* 2: 207–215, 1907–1908.
Hopkins, C. G., *Soil Fertility and Permanent Agriculture,* Ginn and Company, Boston, 1910, p. 201.

manure in the pile will change the decay from aerobic to anaerobic, thus reducing somewhat the waste of gaseous nitrogen while encouraging the simplification of the manurial constituents. Tight floors in the stables and impervious bottoms under the manure pile should considerably diminish leaching losses.

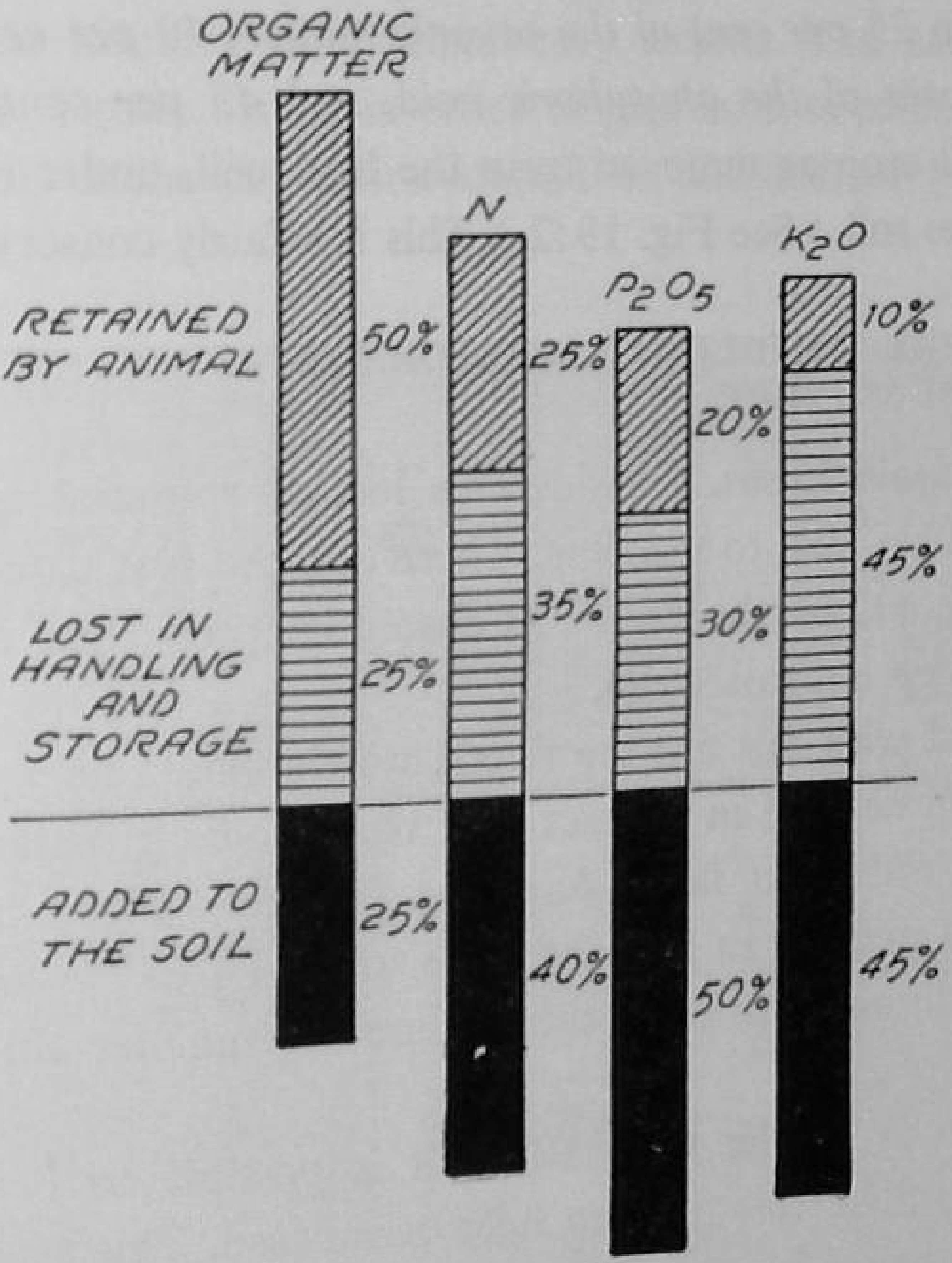


FIG. 19:2. *A tentative representation of the proportion of the organic matter, nitrogen, phosphoric acid, and potash originally present in the food (1) retained by the animals, (2) lost in handling and storage of the manure, and (3) applied to the soil.*

While the figures [12] are extremely variable, it is probable that *one-half* of the *nitrogen, potash,* and *organic matter* and at least *one-third* of the *phosphoric acid* of farm manure are lost even under fairly careful methods of storage. On farms where manure remains outside for several months, the losses will, of course, be higher. Thus, at least one-half of the nutrient

[12] Data respecting manurial losses may be found as follows:

Roberts, I. P., and H. H. Wing, *On the Deterioration of Farmyard Manure by Leaching and Fermentation,* Bulletin 13, Cornell Univ. Agr. Exp. Sta., 1889.

Schutt, M. A., *Barnyard Manure,* Bulletin 31, Canadian Dept. Agr., Cent. Exp. Farms, 1898.

Thorne, C. E., *Farm Manures.* Orange Judd Publishing Company, Inc., New York, 1914.

constituents of the manure may often be wasted. This represents considerably over one-half of the fertilizer value, since the elements removed are those most readily available to plants.

Considering the losses which the food sustains during digestion and the waste of the manure in handling and storage, it cannot be expected that more than *25 per cent of the organic matter, 40 per cent of the nitrogen, 50 per cent of the phosphoric acid,* and *45 per cent of the potash* of the original crop as removed from the land will, under ordinary conditions, reach the soil. (See Fig. 19:2.) This is a fairly conservative estimate.

19:7. PRACTICAL HANDLING AND STORAGE OF FARM MANURE

Reducing liquid losses. Considerable loss of manurial constituents occurs in the stable, due to leaching. Therefore, the first care is to the bedding, which should be chosen for its absorptive properties, its cost, and its capacity to keep animals clean.

Coordinated with this are the floors, which should be tight so that the free liquid will be held in contact with the absorbing materials. Preservation in stalls with tight floors has been for years a common method of handling farm manure in England. The trampling of the animals and the continued addition of litter as the manure accumulates aid in the preservation.

Apply directly to the field. When it is possible to haul the manure directly to the field, this practice is to be advised. This system saves time and labor, and very largely obviates leaching losses since the soluble portions of the manure are carried directly into the soil. Such a practice, however, will not prevent some losses by volatilization.

It should not be assumed that daily spreading will always result in the greatest conservation of nutrients. For example, consider the areas where, during the winter months, manure is spread on frozen ground or on snow over frozen ground. In the spring the snow melts and the water often runs off the land before the soil thaws. This melt water carries much of the soluble potash and nitrogen of the manure with it, especially on land that is quite sloping. As much as about 25 per cent of the potash supplied in manure may be lost in this manner.[13]

Storage in piles. It is often necessary to store manure outside, fully

[13] See Midgley, A. R., and D. E. Dunklee, *Fertility Runoff Losses from Manure Spread during the Winter*, Bul. 523, Vt. Agr. Exp. Sta., 1945

exposed to the weather. When this is the case, certain precautions should be observed. In the first place, the pile should be located on level ground far enough from the eaves of any building so that it receives no extra water in times of storm. (See Fig. 19:3.) The sides of the heap should be steep enough to shed water readily, while the depth of the pile should be such as to allow little leaching even after heavy storms. The earth under the manure may be slightly dished in order to prevent loss of excess water. If possible, the soil of the depression should be puddled, or better, covered with cement.

FIG. 19:3. *Millions of dollars worth of nutrients are lost annually by the careless handling of farm manure. Scenes such as the above are all too common.*

Manure pits. Some farmers, especially if the amount of manure produced is large, find it profitable to construct manure pits of concrete. These pits are usually rectangular in shape with a shed covering. One or even both ends may be open to facilitate the removal of the manure. In such a structure, leaching is prevented by the solid bottom while the roof allows a better control of moisture conditions. By keeping the manure carefully piled and well moistened, decomposition may proceed with a minimum waste. Large losses of nitrogen and especially of carbon (as CO_2), however, will still take place.

Covered barnyards. Another method of storage is in covered barnyards or in sheds where animals are fed and bedded. The floor of such a structure should be more or less impervious. The manure is kept thoroughly packed as well as damp by the animals. This is a common method of handling manure in the fattening of steers in the Middle West and elsewhere and allows a minimum loss.

It is evident from this consideration that well-protected and carefully preserved manure will be higher in available plant nutrients than that carelessly handled. Since hauling directly to the field affords less chance of loss by leaching and fermentation, this mode of handling should be adopted wherever feasible. If storage must be resorted to, the precautions already suggested should be observed insofar as possible.

19:8. ECONOMIC UTILIZATION OF FARM MANURE

Method and rate of application. In the application of manure to the land, the same general principles observed in the use of any fertilizer should be kept in mind. Of these, fineness of division and evenness of distribution are of prime importance. The efficiency of the manure may be raised considerably thereby.

A third important factor is the rate of application. Since the supply of manure is often limited in diversified farming, it is usually better, especially with field crops, to decrease the amounts at each spreading and cover a greater acreage. Thus, instead of adding 20 tons to the acre, 10 tons may be applied and twice the acreage covered. Applications can then be made oftener and a larger and quicker net return realized for each ton of manure.

Not only is there a greater crop yield per ton from the smaller applications but a greater recovery of the manurial fertility in the crops may also result. Ohio experiments [14] show that, in the first rotation after the manure is applied, a 25 to 30 per cent higher recovery may be expected from an 8-ton treatment to the acre than from a 16-ton application.

Manure speader. Evenness of application and fineness of division are greatly facilitated by the use of a manure spreader. This also makes possible the uniform application of small amounts of manure, even as low as 5 or 6 tons to the acre. It is impossible, of course, to spread such small amounts by hand and obtain an even distribution.

[14] Thorne, C. E., and others, *Plans and Summary Tables of the Experiments at the Central Farm*, Circular 120, Ohio Agr. Exp. Sta., 108, 1912.

Surface application *vs.* plowing under. Whether manure should be plowed under or not depends largely on the crop on which it is used. On meadows and pastures it is spread as a top-dressing. With certain other crops, however, it is commonly plowed under. This is particularly necessary if the manure is long, coarse, and not well rotted. If manure is fine and well decomposed, it may be harrowed into the surface soil as is sometimes done with wheat. Obviously, the method of application employed will depend on the crop, the soil, and the condition of the manure.

C:N ratio. In the utilization of farm manure it is well to remember that its addition to the soil in large amounts may widen the carbon-nitrogen ratio. This is likely to be the case if the manure is unusually strawy. The delay in plant growth that is sometimes observed from the use of strawy manure may be due to the reduction of nitrate accumulation induced by the high carbon content of the materials added. If such is likely to be the case, a sufficient interval should elapse between the application of the manure and the planting of the crop in order that nitrification may again be active.

19:9. REINFORCEMENT OF FARM MANURE

Reasons for reinforcement. As already explained, average farm manure contains about five times more readily available nitrogen and potash respectively than active phosphoric acid. (See page 533.) It is thus badly unbalanced. In comparison with a complete commercial fertilizer, there should be at least five times more available phosphoric acid in the manure than is usually present to be sure that its nitrogen and potassium are properly balanced. Hence, in order to obtain the most economical results with manure, liberal applications of phosphorus should be used in the rotation in connection with it. Sometimes, however, part of the phosphatic fertilizer is mixed with the manure before it is applied to the land. This is the practice that is spoken of as *reinforcement.*

Rate of phosphate additions. The amount of phosphatic fertilizers that should be added to a ton of farm manure depends on the acre-rate of application of the latter. Ordinarily from 500 to 600 pounds of 16 to 20 per cent superphosphate or its equivalent are applied to the acre in this way during the course of a field crop rotation. Thus, if 10 tons of manure are spread on an acre, each ton should be reinforced with 50 or 60 pounds of ordinary superphosphate. If 15 tons of manure are applied an acre, the reinforcement may be at the rate of 35 to 40 pounds of super-

phosphate a ton. If raw rock phosphate is used instead, it generally is applied at double the rate of superphosphate because of the less ready availability of the rock.

If the superphosphate is added each day in the stable in the case of dairy cows, 2 pounds per cow will amount to a reinforcement of about 50 pounds to the ton of manure. With this as a gauge any desired rate of superphosphate application to the land may be decided on, provided, of course, the tons of manure that are to go on each acre of land are known in advance. Thus, if the rate of manuring is to be 10 tons, 2 pounds of superphosphate daily per cow would mean the application of 500 pounds of superphosphate to each acre of land receiving the manure.

19:10. CROPS THAT RESPOND TO FARM MANURE [15]

Since manure is available in limited amounts on the average farm and as mineral fertilizers give good results on grass and legumes, it is often considered judicious to reserve most of the manure for other crops of the rotation. This is especially the case when a feed crop such as corn or such cash crops as cabbage, tobacco, cotton, or potatoes are grown.

The top-dressing of the meadows with farm manure is allowable, especially with a new seeding or when the sod is soon to be plowed under for a cultivated crop. When the soil is acid and lime cannot be applied, it is practically necessary to top-dress the new seeding in order to insure a good stand of clover. Manure thus takes the place of lime, in a way, and strengthens and protects the crop. In many communities a large proportion of the farm manure is applied to the meadows, no doubt for the reasons just suggested.

The value of manure in orchards should not be overlooked, especially on sandy soils, as the maintenance of organic matter as well as nitrogen is a vital factor in orchard practice. In most cases, however, the fertility of an orchard soil can be maintained adequately by means of leguminous cover-crops and a nitrogenous commercial fertilizer, thus releasing what farm manure there is for use in the regular field rotation or for vegetables.

With trucking, garden, and greenhouse crops, the applications of large amounts of manure when obtainable have always proved advisable. As a matter of fact, manure when correctly handled, has shown itself one of the best fertilizers for intensive operations. This is due not only to the

[15] See Thorne, C. E., *Farm Manures*, Orange Judd Publishing Company, Inc., New York, 1914, Chaps. 11 and 13.

nutrients carried by the manure, but to the large quantities of easily decomposed organic matter that are at the same time introduced. As large amounts of highly phosphatic fertilizers usually accompany or follow the manure in such cases, direct reinforcing is unnecessary.

19:11. FARM MANURE AND THE MAINTENANCE OF SOIL FERTILITY

The value of farm manure is determined not only by the organic matter it furnishes but especially by the quantity of nitrogen that it supplies. The nitrogen, when released by microbial activity, is used as a nutrient by higher plants. In addition, it makes possible the maintenance of a higher soil organic matter level than would otherwise be the case. Thus, even though farm manure no doubt has a very considerable influence on the physical and biological properties of the soil, it must be considered particularly as a nitrogen fertilizer and to a lesser degree one of potash also.

Viewed in this light the question immediately arises: Can the fertility problems of the representative general or dairy farm be solved by the use of farm manure even if it should be reinforced adequately with superphosphate? The answer, of course, is "No," especially if a more or less permanent fertility system is in operation. There are several reasons for such an answer.

In the first place, hardly one-half of the nitrogen, potash, and phosphoric acid removed from the soil by the crops fed to animals is returned to the land in farm manure. (See Fig. 19:2.) And, of course, not all crops are used for animal food. Thus, the utilization of farm manure alone would obviously result in a gradual reduction of soil fertility unless other sources of nutrients were resorted to. Reinforcement with superphosphate would only delay the evil hour. It is only when farm manure is properly coordinated with lime, commercial fertilizers, and legumes as well as with good tillage, weed elimination, and soil-water and erosion control, that the fullest benefits from this valuable farm by-product are to be realized.

19:12. GREEN MANURES[16]—DEFINED

From time immemorial the turning under of a green crop to better the condition of the soil has been a common agricultural practice. Records show that the use of beans, vetches, and lupines for such a purpose was

16 A full discussion of green-manuring in all of its phases may be found in Pieters, A. J., *Green-Manuring*, John Wiley and Sons, Inc., New York, 1927.

well understood by the Romans, who probably borrowed the idea from other nations. The art was lost in Europe to a great extent during the Middle Ages, but was revived again as the modern era was approached.

This practice of turning into the soil undecomposed green plant tissue is referred to as *green-manuring*. Material so added, if the soil is in a proper condition and well managed, brings about a number of favorable effects and may aid materially in maintaining or raising the crop-producing capacity of a soil.

19:13. THE BENEFITS OF GREEN-MANURING

Supplies organic matter. The influence exerted by green-manuring which is generally mentioned first relates to the organic supply of the soil. When there is a shortage of farm manure, the practice becomes of special importance since roots and other crop residues may not be adequate to maintain the humus content of the land. Even when farm manure is available, a green-manuring crop now and then may do much toward sustaining a suitable amount of organic matter as well as activate that already there.

The humus compounds resulting from the decay of green manures without doubt increase the adsorptive capacity of the soil. They promote aeration, drainage, and granulation—conditions that are extremely important to successful plant growth. In fact, organic matter is one of the most important factors in determining the tilth of any soil. (See page 69.)

Addition of nitrogen. The plowing under of a green manure not only adds organic carbon to the soil but also returns soil nitrogen. The amount of nitrogen may be large or small, depending on conditions. If the crop turned under is a legume and the nodule organisms have been active, the store of soil nitrogen may be thereby increased. The organic matter content is also augmented since the amount of soil humus finally formed is determined to a considerable degree by the amount of organic nitrogen present (see page 169).

Biochemical benefits. The organic material added in green manures also acts as a food for soil organisms, and tends to stimulate biological changes sometimes to a marked degree.[17] Such biochemical action is of special

[17] For the activating influence of green manures, see Lewis, R. D., and J. H. Hunter, "The Nitrogen, Organic Carbon and pH of Southeastern Coastal Plain Soils as Influenced by Green-Manuring Crops," *Jour. Amer. Soc. Agron.*, 32: 586–601, 1940.

consequence in the production of carbon dioxide, ammonium, nitrates, and perhaps other simple compounds. The response of the general-purpose flora of the soil and of the Azotobacter to carbonaceous and nitrogenous materials is well known. Even in peat soils, made up largely of organic matter, organisms may be definitely activated by the turning under of a green-manuring crop.

Conservation and availability of nutrients. A green-manuring crop while vegetative exerts a conserving influence on the nutrients of the soil since it takes up soluble constituents that might otherwise be lost in drainage or by erosion. In this respect it functions as a *cover-crop*.[18] The presence of a green manure on the soil at a time when it might otherwise be bare is highly desirable. Besides this, green manures, especially those with long roots, carry nutrients upward from the subsoil, and when the crop is plowed under these constituents are left nearer the surface.

The increased availability of the inorganic constituents of the soil is a phase that should not be forgotten in this connection. Jensen [19] found that the addition of 3 per cent of green manure to the soil raised the solubility of lime and phosphoric acid 30 to 100 per cent. This was over and above the mineral constituents which came directly from the decomposing green crop. Potassium, magnesium, and iron may also be markedly influenced in the same manner. In fact, the potash problem of some soils is solved, at least temporarily, by the activity of the soil organic matter.

19:14. INFLUENCE OF LEGUMINOUS GREEN MANURES ON SOIL NITROGEN

When a nonlegume is turned under as a green manure, nitrogen originally in the soil is merely returned in an organic form. There is no gain. But if a legume is so utilized, there is a possibility of increasing temporarily the soil nitrogen to the extent of the symbiotic fixation. Since an increase in the organic nitrogen of the soil means an increase in fertility as well as a possible rise in humus, the probable magnitude of the fixation is worthy of some attention.

[18] A *cover-crop* is one planted for the purpose of covering or protecting the soil at certain times of year, especially from erosion hazards.

A *catch-crop* is one that follows the main crop. It must be rapid in growth as it can occupy the soil only a relatively short time. Both a cover-crop and a catch-crop may, on occasion, be used as a green manure.

[19] Jensen, C. A., "Effect of Decomposing Organic Matter on the Solubility of Certain Inorganic Constituents of the Soil," *Jour. Agr. Res.*, 9: 253–268, May, 1917.

Amounts of nitrogen fixed. Data have already been cited (page 461) which indicate that the nodule organisms of a vigorous crop of alfalfa might fix from 200 to 250 pounds of nitrogen an acre. Comparable figures for red clover are perhaps 100 to 150 pounds an acre. Soybeans compare rather well with red clover but hairy vetch and field beans ordinarily will acquire from the air only a half or a third as much nitrogen. If these crops are turned under, the soil, of course, gains in organic nitrogen to the extent of the microbial fixation.

A rough-and-ready method of calculating this fixation is based on the assumption that the nitrogen present in the tops of well-inoculated legumes represents the amounts fixed by the symbiotic bacteria.[20] It must be admitted, however, that this provides an extremely uncertain basis for estimation, yet it gives a rough idea of the extra nitrogen that might be acquired by the soil. For instance, a ton of dry red clover contains from 40 to 50 pounds of nitrogen. If a green-manuring crop equivalent to 2 tons of such dry substance an acre should be turned under, there would be a gain in soil nitrogen of 80 to 100 pounds.

Increase in humus. Assuming the latter figure and a carbon-nitrogen ratio of 12 to 1, this amount of organic nitrogen should support an increase in humus of perhaps 1,800 pounds if it were all used in this way. Concurrently, of course, there is the stimulation of soil organisms of all kinds. This activation, common to all green manures when properly used, is especially characteristic of those of a leguminous nature.

19:15. THE DESIRABLE CHARACTERISTICS OF A GREEN MANURE

An ideal green-manuring crop should possess three major characteristics: (1) rapid growth, (2) abundant and succulent tops, and (3) the ability to grow well on poor soils. The more rapid the growth, the greater the chance of fitting such a crop into the rotation and of using it economically as a means of soil improvement. Abundant tops and roots are, of course, a necessary feature. And as already suggested, the higher the moisture content of the green manure the more rapid is the decay and the more quickly are benefits obtained. As the need of organic matter is especially urgent on poor land, a hardy crop has great advantages.

When other conditions are equal, it is better to make use of a leguminous

[20] Hopkins, C. G., *Soil Fertility and Permanent Agriculture*, Ginn and Company, Boston, 1910, p. 217.

green manure in preference to a nonleguminous one, because of the nitrogen gained by the soil and the organic activity it promotes. A little additional nitrogen is sometimes of tremendous importance.

However, it is often difficult to obtain a catch of some legumes and they may be so valuable as animal feed, that it is poor management to turn the stand under. Again, the seeds of many legumes are expensive, almost prohibiting the use of such crops as green manures. Moreover, some legumes do not fit into the common rotations in such a way as to be turned under conveniently as a green manure.

19:16. PLANTS SUITABLE AS GREEN MANURES

Some of the plants utilized in the various parts of the United States as green manures are listed in Table 19:1. Their value, of course, depends in part on climate, some of those mentioned being unsuited to northern regions and vice versa.

Table 19:1. List of Possible Green Manuring Crops

Legumes		*Nonlegumes*	
Southern Section Especially	*Wide Range*	*Wide Range in Most Cases*	
Crimson clover	Alfalfa	Rye	Ryegrass
Bur clover	Red clover	Oats	Sudan grass
Lespedeza	Sweet clover	Barley	Mustard
Crotalaria	Soy bean	Millet	Rape
Smooth vetch	Canadian field pea	Buckwheat	Weeds
Austrian winter pea	Cowpea	Wheat	Winter oats and barley

The growing of two crops together for green-manuring purposes is sometimes recommended. If properly chosen in respect to growth habits, climatic adaptation, and soil requirements, the advantages are noteworthy. Not only can larger amounts of green material be produced but also, if one of the crops is a legume, nitrogen fixation may be taken advantage of. Also one crop may offer physical support to the other, a factor of no mean importance when dealing with plants that tend to lodge.

Oats and peas, and rye and vetch are excellent examples of such green-manure combinations. The two nonlegumes in these cases are highly desirable because of their rapid, abundant, and succulent growth and because they may be accommodated to almost any rotation. These nonlegumes

are hardy and will start under adverse weather conditions and in a poorly prepared seedbed. They are thus extremely valuable on poor soils. Moreover, their influence is notably enhanced by sowing a legume with them. In any case the mixtures should be plowed under when at mid-growth or soon after, as at that time their carbon-nitrogen ratio is comparatively narrow.

19:17. THE PRACTICAL UTILIZATION OF GREEN MANURES

The turning under of green crops must be judicious in order that the soil may not be clogged with too much undecayed matter. Once or twice in a rotation is usually enough for such treatments. Good drainage should always be assured as aeration is of vital importance in the proper decay of plant residues in the soil.

In regions of low rainfall. In regions where rainfall is scanty, great caution must be observed in the use of green manures. The available moisture that should go to the succeeding crop may be used by the green manure itself or in the processes of decay, and the soil left light and open. In the drier portions of the United States, it is doubtful whether green manures are of any real value because of this.

Conditions at time of turning. It is generally best to turn green crops under when their succulence is near the maximum and yet at a time when suitable tops have been produced. With most green manure this occurs at about or a little beyond the half-mature stage. A large quantity of water is carried into the soil when the crop is in this condition, and the over-all draft on the original soil moisture is less. Moreover, the carbon-nitrogen ratio of the green manure is comparatively narrow at this time.

Again, the succulence encourages a rapid and more or less satisfactory decay, with the maximum production of humus and other products. The plowing should be done, if possible, at a season when a plentiful supply of rain occurs. The effectiveness of this type of manuring is thereby much enhanced as the moisture conditions are such as to insure a rapid and effective decomposition.

Whether to fall- or spring-plow a green-manuring crop is of practical concern and is decided largely by such factors as climate, the nature of the soil, and the crop used. Fall plowing seems to be of some advantage in the northern states as measured by nitrate accumulations during the following summer. The reverse seems to be true farther south where the winters are milder and shorter and where the spring and summer seasons

are longer. Whether the soil is sandy or clayey must also be considered.

Rotation considerations. Whether or not a crop can be used advantageously as a green manure often is determined by the character of the rotation. In the northern states, due to the shorter season, it is often somewhat of a problem whether a green manure may be introduced without seriously interfering with the regular crops of the rotation. Not only is the period for the growth of the green manure very short, but the time interval between the turning under of the green substance and the planting of the next crop is often inadequate. In our southern states this disadvantage is not encountered to such an extent, since the season is much longer and the rotation less likely to offer interference.

19:18. GREEN-MANURING AND THE MAINTENANCE OF SOIL FERTILITY

It cannot be emphasized too strongly that green manuring is only one of the several practices that may be employed in an attempt to maintain, or partially maintain, the fertility of arable lands. Moreover, it usually is the last of the various methods so employed to be resorted to. Crop residues, especially roots, and farm manure under ordinary conditions supply most of the organic matter found in mineral arable soils, and if the nitrogen level is high, these should suffice as far as organic matter maintenance is concerned. Whether or not green manures are used should depend in part on the adequacy of these sources of plant tissue. The plowing under of green plants, therefore, may be considered as a supplementary measure, very important in some cases but ordinarily not so essential in the general fertility scheme as are certain other practices.

CHAPTER

20 The Fertility Management of Mineral Soils

WHILE MOST of the fundamental facts and conceptions regarding the nature and properties of soils and their plant relationships have been presented, they have not been adequately correlated in a practical way. It seems desirable at this point, therefore, to interrelate these facts and ideas in such a manner as to establish a general scheme of fertility management flexible enough to meet any situation.

The maintenance of soil fertility at a satisfactory level while at the same time producing profitable crops is an intricate problem. It is related to and depends upon many variable factors not strictly of a fertility nature. These factors definitely govern the scope of the various fertility problems and are in turn affected by soil fertility maintenance. Consequently, the *over-all soil management* requirements must be discussed briefly before narrowing our attention to the problems of soil fertility.

20:1. THE FIVE MAJOR FEATURES OF GOOD SOIL MANAGEMENT

In outlining a good system of soil management five major features usually are cited. Of these *good tilth* deserves first consideration. (See page 75.) This means a suitable condition of the soil physically and implies in addition a satisfactory regulation of soil moisture and soil air. The proper maintenance of soil humus and the encouragement thereby of granulation are the first requisites of tilth. Plowing and cultivation should loosen the soil with a minimum of soil aggregate destruction. These operations should be properly timed, especially with respect to soil moisture. Good tilth also is a primary factor in erosion control and in a broad way is related to crop ro-

tation. A good rotation should preserve or perhaps even enhance soil aggregation.[1]

The *control of weeds,* a second major factor in soil management, is also closely associated with good tilth. At certain times during the growing season tillage is practiced almost wholly for the control of weeds. Some weeds, however, such as mustard, quack grass and bindweed, cannot be discouraged effectively by cultivation, and other means must be employed. Of these, herbicide sprays seem most effective. (See page 224.) Weeds, by using moisture and nutrients that otherwise might go to the crop, undoubtedly are one of the most serious problems that confront many farmers.

The control of *plant diseases* and *insect pests* is in certain cases a phase of soil management. Many insects and disease organisms pass a part, or the whole, of their life cycle in the soil. The handling of the soil may greatly affect their virulence. The time of plowing the land, the order of the crops grown, the intervals between the successive crops, the burning of residues, and the addition of chemicals are illustrative of the relation of soil management to insect and disease control. The fall plowing of the land to reduce cutworm activity and the burning or plowing under of cornstalks to suppress the corn-borer organisms are specific examples. The addition of sulfur to lower the pH in potato-scab control and the use of hydroxide of lime to make the soil alkaline in the suppression of the club root disease of cabbage may also be cited.

A *proper sequence of crops* is also in part a feature of soil management since the rotation employed greatly influences the soil physically, chemically, and biologically. For instance, sod crops tend to conserve nitrogen, encourage humus accumulation, and promote granulation. Cultivated crops, on the other hand, encourage organic decay and increase the losses of nutrients in drainage. Whether a crop is a legume or a nonlegume is an important consideration. Again, erosion control is in part a question of crop selection. In short, no system of soil management is complete until a suitable rotation has been decided upon. The role of crop rotation in soil fertility maintenance will be discussed later. (See page 567.)

[1] Experiments on Marshall silt loam at Clarinda, Iowa, show that soil aggregation in 1949, after an eight-year comparison of continuous corn with a rotation of corn-oats-meadow, was about twice as high on the latter set of plots. Moreover there was a positive correlation between corn yields and degree of granulation.

Van Bavel, C. H. M. and F. W. Schaller, "Soil Aggregation, Organic Matter, and Yields in a Long-Time Experiment as Affected by Crop Management," *Proc. Soil Sci. Soc. Amer.,* 15: 399–408, 1950.

A good system of soil management should, above all, provide an adequate supply of *available plant nutrients.* This is the fifth major requisite. If the fertility of the soil is high, the situation is comparatively simple. The good tilth and adequate aeration and moisture control already emphasized should make it possible for plants to absorb the nutrients in proper amounts. That is, in a fertile soil chemical and biological processes are so regulated and encouraged as to supply sufficient quantities of nitrogen, phosphoric acid, potash, lime, and other constituents necessary for satisfactory crop growth.

But on the other hand, if any one of these essential elements is lacking, it must be added. As most land soon requires such additions, the maintenance of a well balanced fertility has become a most important and widespread problem in the management of soils, particularly in humid regions. Even in arid regions perhaps the only feature holding a priority rating is water supply.

20:2. NUTRIENT GAINS AND LOSSES AS THEY INFLUENCE FERTILITY MANAGEMENT

All the elements essential for the growth of plants are involved in the fertility management of a soil. Supplying each of these elements entails problems which are unique and which often differ markedly from the supply problems of the others. One basic principle is essentially the same, however, for all of these constituents; *the maintenance of optimum amounts of the nutrient elements can be realized only by keeping a favorable equilibrium between gains and losses.* Here, again, excesses as well as deficiencies must be considered. Also, the gains and losses refer directly only to those forms of a given element which are readily *available* for plant growth. For example, the solution of phosphorus from insoluble minerals is just as valid a gain as is the phosphorus supplied by fertilizers. Conversely, the reversion of added phosphates to insoluble forms is an actual loss of available phosphorus, even if only a temporary one. (See Fig. 20:3.)

20:3. FERTILITY MANAGEMENT IN OUTLINE

The major features that must be looked to in the successful management of soil fertility are seven in number. When properly coordinated they may be considered as a *system* of fertility maintenance. They are listed below with some of the means by which they are effectively attained in practice.

1. Adequate supply of nitrogen from
   - Crop residues
   - Farm manure
   - Legumes
     - Regular crop
     - Green manure
   - Rain and snow
   - Nitrogen fertilizers
2. Addition of soil organic matter by means of
   - Crop residues
   - Farm manure
   - Green manure
     - Legume
     - Nonlegume
3. Application of lime if necessary
   - Calcic or dolomitic limestone is most commonly used.
4. Addition of phosphorus
   - Superphosphate or other phosphatic fertilizers
5. Provision for available potassium by means of
   - Farm manure
   - Crop residues
   - Potash fertilizers
6. Sulfur deficiencies are met with
   - Flowers of sulfur or gypsum or superphosphate
   - Sulfur compounds carried in rain and snow
7. Application of trace elements
   - As separate salts or in mixtures

20:4. THE NITROGEN DEFICIT—HOW MET

The relationship between the gains and loss in available soil nitrogen is shown in Figure 20:1. A few generalizations on expected gains and losses should be helpful in studying this diagram. For example, with field crop rotations, it has been shown that nitrogen losses by leaching and volatilization are approximately offset by rainfall and azofication additions. This leaves the removal of nitrogen by crops and erosion as the two major deficits to be met. The combined losses from arable soils probably amount to at least 75 or 100 pounds of nitrogen per acre yearly. Let us review briefly the most effective means of meeting this deficit.

Crop residues—legumes. The return to the soil of plant materials, including roots and tops, is an important, but often overlooked, source of nitrogen. The plant tissues thus returned may be by-product crop residues remaining after the harvest or they may be green manure crops grown specifically to conserve or add nitrogen. In either case the probability of actually adding

to the available soil nitrogen supply is greatly increased if the crop is a legume. A crop of red clover, sweet clover or vetch, for example, may contain from 100 to 150 pounds of nitrogen an acre, much of which is fixed by microorganisms associated with their roots.

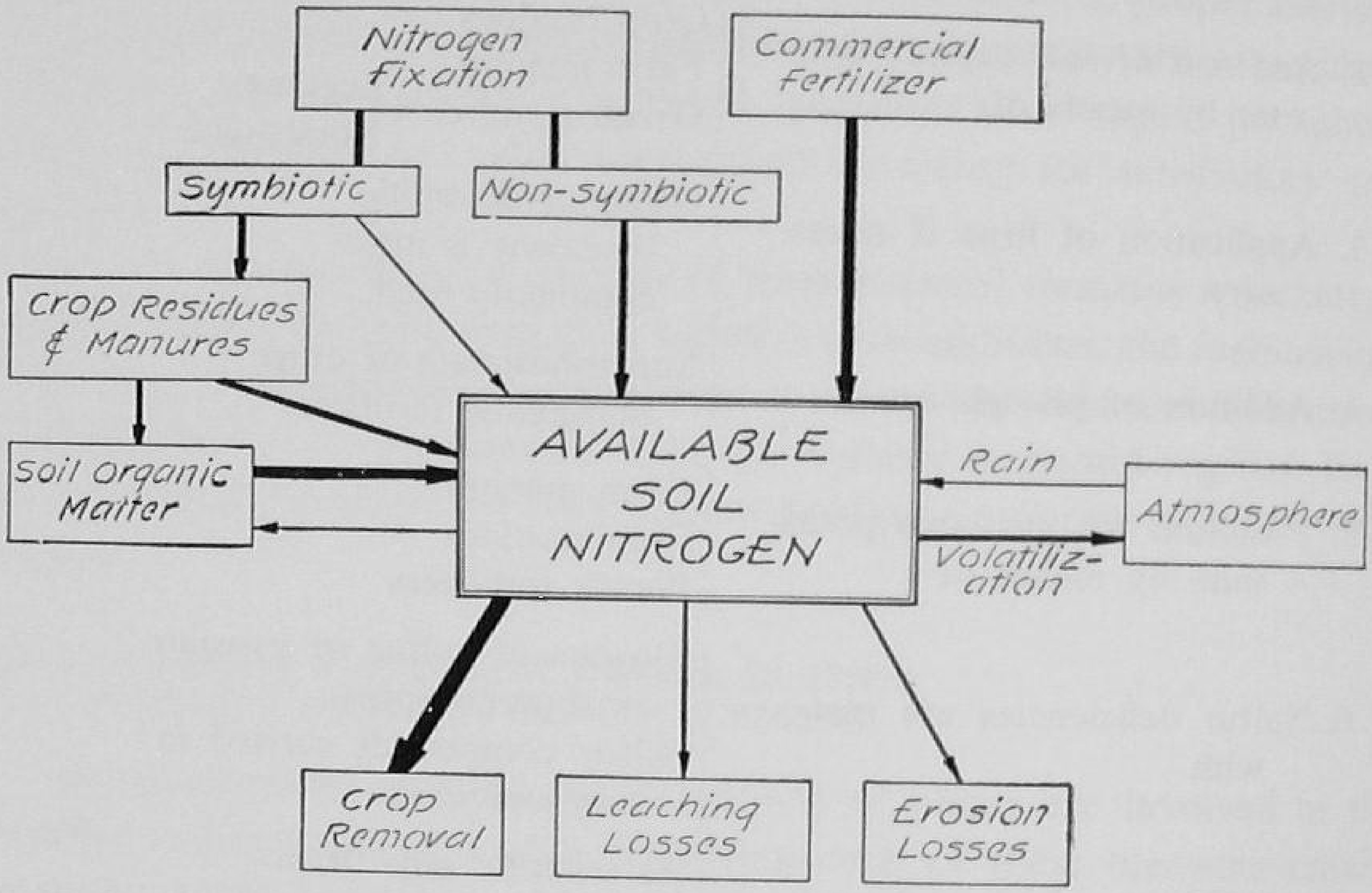


FIG. 20:1. *Diagram showing the major gains and losses of* available *soil nitrogen. The width of the arrows indicates roughly the magnitude of the losses and the addition often encountered. It should be emphasized that the diagram represents average conditions only and that much variability is to be expected in the actual and relative quantities of nitrogen involved.*

Farm manure. Another method used on many farms to return nitrogen is that of applying barnyard manure. This by-product carries approximately 10 pounds of nitrogen to the ton and is too valuable to be neglected. Assuming a 10-ton application an acre once in a five-year rotation, the return to land so treated would amount to 20 pounds of nitrogen an acre yearly. While by no means meeting the nitrogen deficit, farm manure narrows it considerably.

Nitrogen from humus and commercial fertilizers. The methods of supplying available nitrogen so far considered generally fall short of replacing the annual losses of this element from soils. Much of this deficiency has been met in the past by the release of nitrogen from decaying soil organic matter. The rate of release from this form apparently was sufficiently rapid when virgin soils were first cultivated to meet crop demands. In time, however,

the soil organic matter became reduced in most cases to the point where the rate of nitrogen release from this source was insufficient to obtain maximum crop yields. Consequently, commercial fertilizers were turned to in an effort to maintain a satisfactory supply of available nitrogen. Today such materials not only supplement the other methods of supplying this element, but in many cases they furnish a major supply. In the future, such sources probably will become even more important.

20:5. THE MAINTENANCE OF ACTIVE SOIL ORGANIC MATTER

The nitrogen control of organic matter. Soil humus accumulation is essentially a nitrogen problem, since the nitrogen of the soil organic matter exerts a marked control on the amount of humus that results. This is because of the relatively constant organic matter-nitrogen ratio. Under ordinary conditions in humid region cultivated soils, the humus attains a ratio of roughly 20 to 1 with the nitrogen present. The greater the amount of organic nitrogen, the higher will be the organic level maintained in mineral soils. The various means of supplying nitrogen cited above thus become doubly significant in practical agriculture.

Organic matter level. As to the amount of humus that should be maintained in any particular soil, a statement made on page 180 can well be repeated. "Since the rate at which carbon is lost from the soil increases very rapidly as the organic content is raised, the maintenance of the humus at a high level is not only difficult but also expensive. It is, therefore, unwise to hold the organic matter above a level consistent with crop yields that pay best. Just what this level should be will depend on climatic environments, soil conditions, the particular crops grown and their sequence." (See also Fig. 6:9, page 180.)

Activity of organic matter. The activity of the soil organic matter is usually even more important than the actual amount of this constituent present. Many productive soils possess much less nitrogen and organic matter than those in the same community whose crop yields are considerably lower. The analysis of the Ontario loam, a soil of high productivity, and that of the Volusia salt loam, naturally a rather poor soil, well illustrate this point (Table 20:1).

A major difference between these two soils is the amount of active lime, which governs in part the effectiveness both of the nitrogen and the organic matter. The poor drainage of the Volusia is also a vital factor. In spite of

the larger amounts of nitrogen and humus in the Volusia silt loam, their turnover, due to the inadequate supply of lime and the slow drainage, is too sluggish to meet the needs of most crops. Other unfavorable physiological conditions no doubt grow out of the lack of lime and poor aeration.

Table 20:1. Percentage Composition of Ontario Loam and Volusia Silt Loam as Sampled in New York (The Figures Are Averages of Twelve Analyses in Each Case) [2]

Constituents in Total	*Ontario Loam*	*Volusia Silt Loam*
Organic matter (N X 20)	3.20	5.00
Nitrogen (N)	0.16	0.25
Phosphoric acid (P_2O_5)	0.11	0.16
Potash (K_2O)	1.98	2.16
Magnesia (MgO)	0.74	0.80
Lime (CaO)	1.04	0.40
Sulfur trioxide (SO_3)	0.14	0.19

20:6. THE IMPORTANCE OF CALCIUM AND MAGNESIUM

The major means by which available calcium and magnesium are increased or decreased in soils are shown diagrammatically in Figure 20:2.

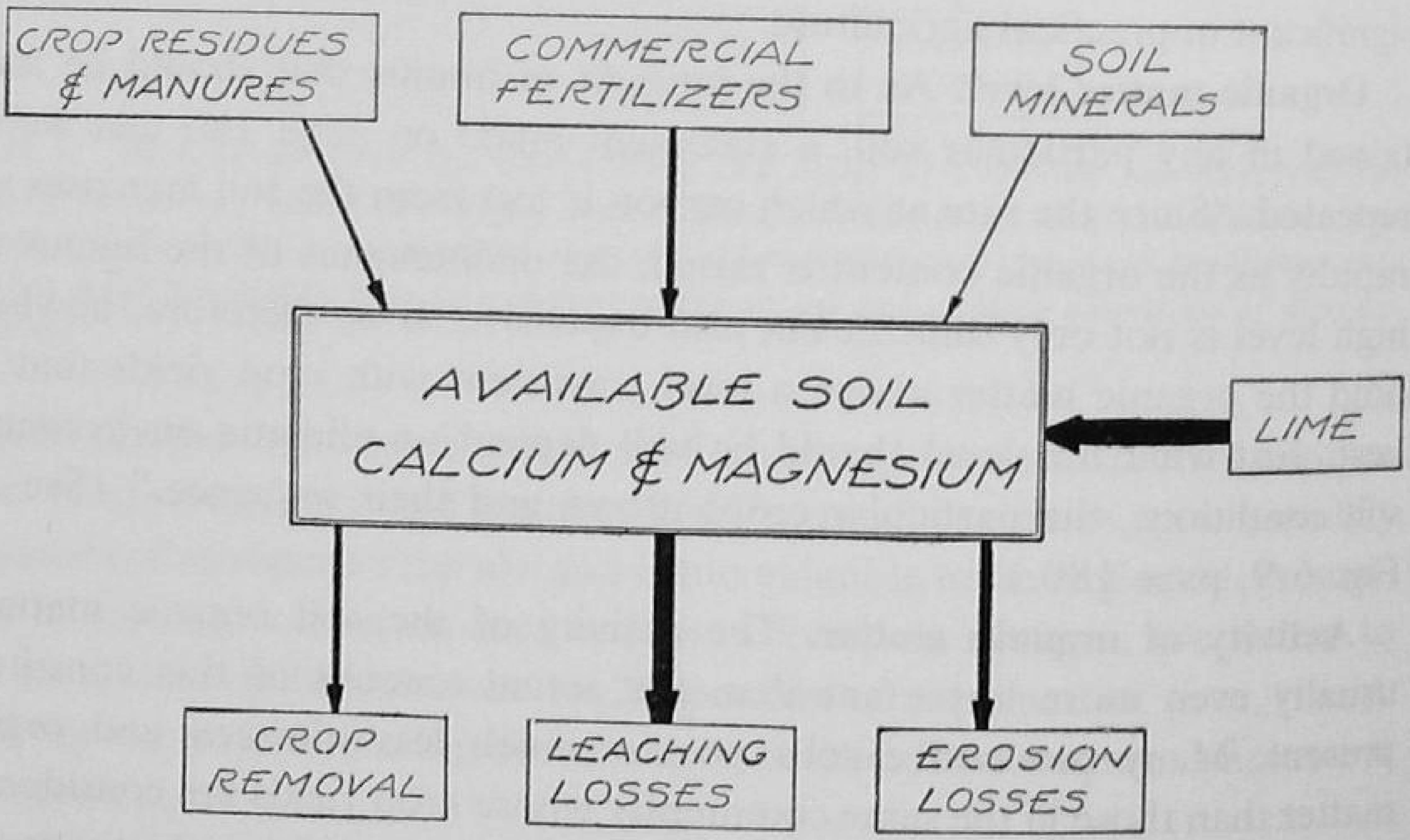


FIG. 20:2. *A schematic representation showing the important ways by which available calcium and magnesium are supplied to and removed from soils. The major losses are through leaching and erosion. These are largely replaced by lime and fertilizer applications. Additions in the latter form are much higher than is generally realized due to the large quantities of calcium contained in superphosphates.*

[2] Bizzell, J. A., *Chemical Composition of New York Soils,* Bulletin 513, Cornell Univ. Agr. Exp. Sta., 1930.

In contrast to the situation in respect to nitrogen, the contents of these elements in plants is comparatively low. Consequently, their loss through crop removal as well as their addition through crop residues and farm manure are correspondingly small.

Fertilizer and soil mineral sources. Although the contents of these two elements in mixed fertilizers are not usually guaranteed, they are often furnished in significant quantities in these materials. For example, calcium is an important constituent of such fertilizers as superphosphate, rock phosphate and calcium cyanamid. Magnesium may be added in special fertilizers as sulfate of magnesia or in the dolomite commonly carried by non-acid forming fertilizers. One would also expect small quantities of available calcium and magnesium to be released by the continuous but slow weathering of certain complex soil minerals.

Leaching and erosion losses vs. liming. Although the changes in available calcium and magnesium cited above are important, a very large proportion of the turnover of these elements is concerned with two other major phases. These are (1) losses of these constituents through leaching and erosion, and (2) their addition in various liming materials.

The combined losses of these nutrients through erosion and leaching often are as great as 500 pounds of $CaCO_3$ equivalent per acre each year. This drain is worthy of consideration because of the deficiencies of calcium and magnesium which it may cause. Even more important, however, are the indirect effects of such losses on soil properties, such as percent base saturation, pH, biological activity, and nutrient availability. Thus, liming practices are used to maintain a favorable physiological condition as well as for nutritional reasons.

It should by all means be remembered that lime is not to be used carelessly as a cure-all but is to be applied judiciously. Too much lime or lime for the wrong crop may be just as bad as the failure to enlist its benefits when they are possible. Chemical tests, especially a determination of soil pH, are indispensable in making lime decisions. The choice of lime to be used should also be carefully made, especially where magnesium deficiencies are suspected.

20:7. THE MAINTENANCE OF AVAILABLE PHOSPHORUS

The maintenance of an available supply of phosphorus is perhaps even more difficult than that of nitrogen or organic matter. A glance at the diagram in Figure 20:3 verifies this fact. This diagram also shows that the

factors affecting the quantity of available phosphorus in soils differ markedly from those concerned with the other nutrients. The removal of phosphorus by growing plants is small compared to that of the other so-called "fertilizer" elements, nitrogen and potassium. Consequently, the loss of this element through crop removal is not excessive nor is the return of phosphorus in crop residues of major importance. Because of the relative insolubility of soil phosphorus compounds, the leaching of this element is essentially nil. Erosion losses are also small, especially when compared to those of potassium, calcium, and magnesium.

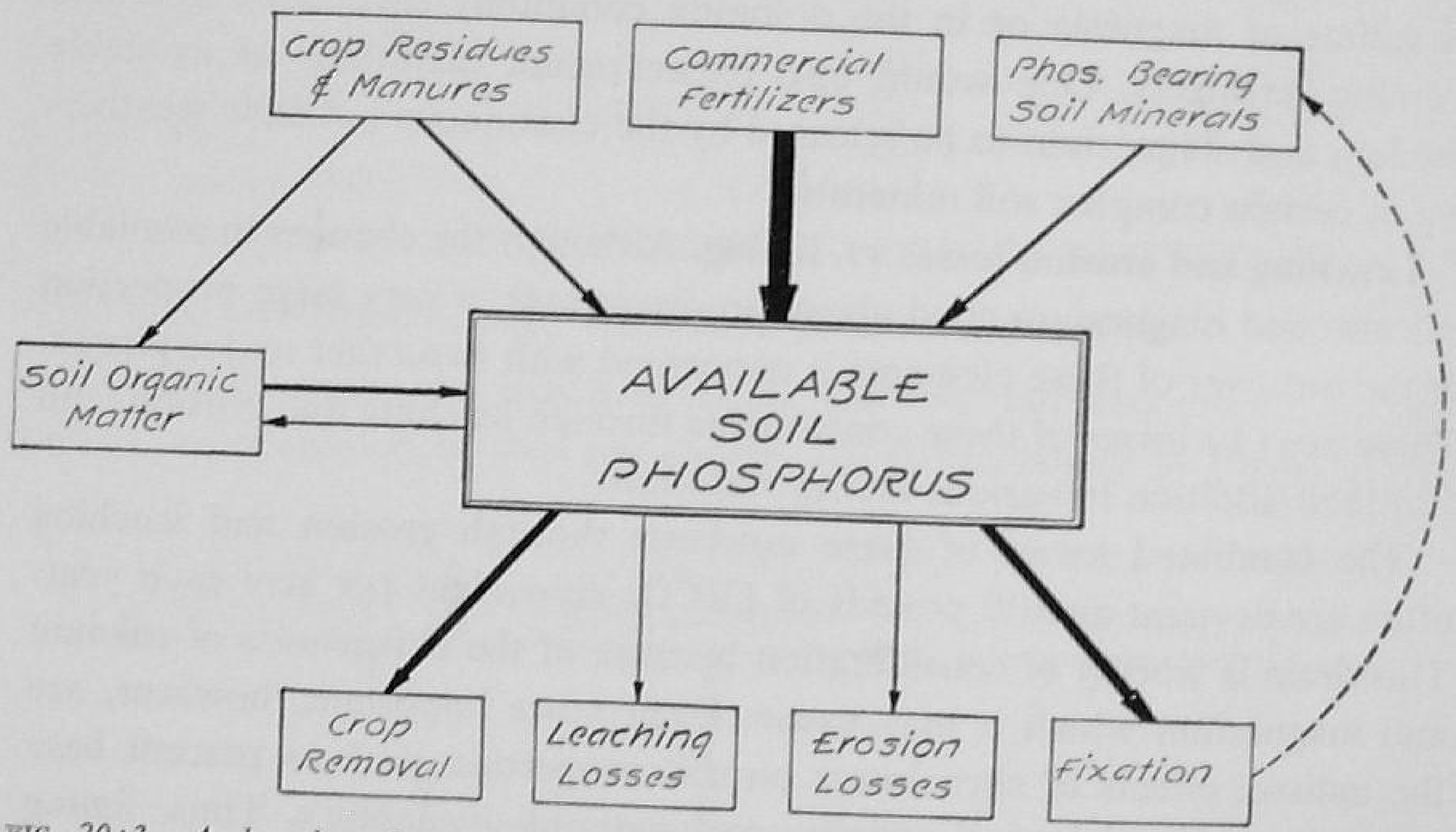


FIG. 20:3. *A drawing showing how the available phosphorus level in a soil is depleted and replenished. Note that the two main features are the addition of phosphate fertilizers and the fixation of this element in insoluble forms. It should be remembered that the amount of available phosphorus in the soil at any one time is relatively small, especially when compared to that of calcium, magnesium, and potassium. For the availability of soil phosphorus, see Fig. 17:1 on page 473.*

A twofold program. Maintaining sufficient available phosphorus in a soil thus largely narrows down to a twofold program: (1) the addition of phosphorus containing fertilizers, and (2) the regulation in some degree of the fixation in the soil of both the added and the native phosphates. For many years phosphatic fertilizers have been a standard and effective recommendation. There are only a few soils which do not give or have not given a crop response to available phosphorus applications. Today commercial fertilizers thus supply most of the phosphorus available to crop plants.

Unfortunately, most of the added phosphates do not long remain in an available form. Depending on the soil pH, they are converted to either iron and aluminum compounds (in acid soils) or calcium compounds (in neutral and alkaline soils). In either case much of the phosphorus is fixed in the form of insoluble minerals from which this element is released very slowly. (See Fig. 17:2, page 478.) Judicious liming practices which will maintain intermediate pH values (6.0 to 7.0) result in a minimum of phosphorus fixation in the above forms and consequently promote maximum availability to plants. The regulation of soil pH is thus a phase of phosphate management that must not be neglected. (See Fig. 14:4, page 405.)

20:8. ADEQUATE AVAILABLE POTASSIUM

Mineral soils, other than those of a markedly sandy nature, contain large stores of potassium. The potash figure for the representative mineral soil is approximately 40,000 pounds to the acre-furrow-slice, not to mention the vast stores of this constituent in the subsoil root zone. In spite of this fact, however, at any one time only a few hundred pounds per acre of available potassium at most are found in an average soil. Obviously, the potash problem of the average soil is not a question of totals but of availability.

Potassium losses and gains. The problem of maintaining soil potassium is outlined diagrammatically in Figure 20:4. As was the case for each of the nutrients so far discussed, certain features of the problem are different from those of any other element. Crop removal of potash generally exceeds that of the other essential elements with the possible exception of nitrogen. Annual losses from plant removal as great as 100 pounds K_2O per acre are not uncommon, particularly if the crop is a legume and is cut several times for hay. As you might expect, therefore, the return of crop residues and manures is very important in maintaining soil potash. As an example, ten tons of average barnyard manure supplies about 100 pounds of potash, fully equal to the amount of nitrogen thus supplied.

The annual losses of available potassium by leaching and erosion greatly exceed those of nitrogen and phosphorus. They are generally not as great, however, as the corresponding losses of available calcium and magnesium. The available potassium depletion by erosion assumes considerable importance when we consider that *total* potassium removal in this manner generally exceeds that of any other major nutrient element. The loss of

potential sources of available potassium (soil minerals) cannot but eventually be serious.

Increasing use of potash fertilizers. In the past potash added in the form of fertilizers has been considered largely as a supplement to that returned in crop residues and that obtained from the slowly available forms of potas-

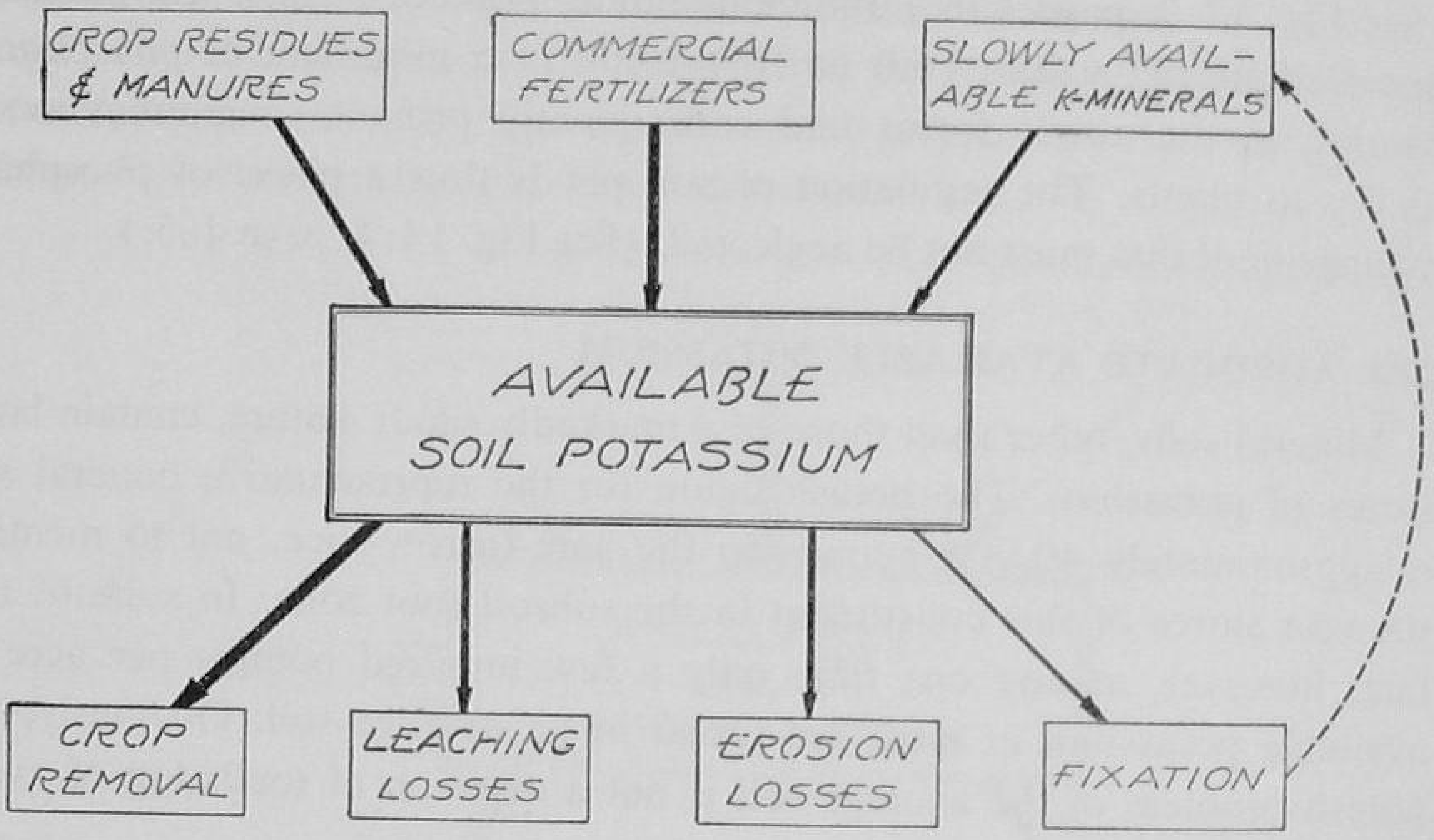


FIG. 20:4. *Gains and losses in* available *soil potassium under average field conditions. The approximate magnitude of the changes is represented by the width of the arrows. For any specific case the actual amounts of potassium added or lost undoubtedly may vary considerably from the above representation.*

As was the case with nitrogen and phosphorus, it is well to note the increasing importance of commercial fertilizers in meeting crop demands. Also, it should be pointed out that the fixation and release by potash bearing minerals will be much greater if soils contain appreciable quantities of minerals such as illite, a clay that is especially high in total and exchangeable potash. For the various forms of potassium in soils and their relative magnitude and relationships, see Fig. 17:5 on page 489.

sium carried by soil minerals. This is still the case on many soils high in slowly available potassium.

On other soils, however, fertilizer potash is now depended upon to supply most of that needed for crop production. This is especially true in cash crop areas and in regions where sandy soils are prominent. Even in some heavier soils, the release of potassium from mineral form is much too slow to support maximum plant yields. Consequently, increased usage of commercial potash must be expected if yields are to be increased or even maintained.[3]

[3] A 5–10–10 is now considered as a sort of general purpose fertilizer rather than the 5–10–5 so popular several years ago. This shift in preference is good evidence of the growing importance of potash in soil fertilization.

20:9. SULFUR DEFICIENCY

Although sulfur is mentioned specifically in the scheme of fertility management presented on page 555, this nutrient usually is taken care of more or less incidentally by the type of soil management in vogue and may not need special attention. Considerable sulfur is added to arable soils in crop residues, green manures, and farm manure, the latter carrying perhaps 5 or 10 pounds a ton. Besides this, appreciable amounts often are added by rain and snow, the quantity ranging from a few pounds an acre annually to as much perhaps as 100 pounds in extreme cases. Another automatic addition is that absorbed from the atmosphere by the soil. (See page 509.) This is thought at times to equal the amount brought down by rain and snow.

Moreover, such fertilizers as sulfate of ammonia, sulfate of potash, and ordinary superphosphate carry appreciable amounts of sulfur. Since the latter fertilizer is approximately one-half gypsum, 100 pounds will supply about 12 pounds of combined sulfur, enough for an acre of the average crop. In the light of such figures, it would seem that soil sulfur, except in certain cases, is not likely to be an element that calls for an unusual amount of attention. Routine fertility practices in most cases should automatically take care of this constituent.

20:10. THE TRACE ELEMENTS

Trace-element fertilization is a phase of soil management that is destined to great development. The reason is obvious. Our fertility efforts for years have had to do largely with nitrogen, phosphorus, potassium, and lime. In many cases constant cropping with such an unbalanced replacement has gradually exhausted the small amounts of available copper, zinc, manganese, and boron below the current needs especially of certain crops. At present, plant malnutrition due to trace-element deficiencies are becoming apparent in localized areas wherever crops have been grown for any great length of time. This is especially true in eastern and central United States.

Already crop specialists are familiar with the symptoms of trace-element deficiencies [4] and, as time goes on, the growers themselves will learn them for the relatively small number of crops with which they, individually, are

[4] For literature dealing with trace element deficiencies, see *Hunger Signs in Crops*, American Society of Agronomy and the National Fertilizer Association, Washington, D. C., 1949.

concerned. The fertilizer salts that commonly are used have already been considered (page 511) and gradually the rates of application will be standardized for individual crops and particular soil types.

It is especially important to note here that no fertility diagnosis is now complete without a consideration of the trace elements. So long as even one is deficient, the crop will be unable to make adequate use of the other nutrients no matter how liberally the latter are supplied or how favorable environmental conditions may be. A nutrient ration can be just as seriously unbalanced because of the lack of a mere trace of zinc or boron as from a deficiency of nitrogen or potash.

20:11. THE FLEXIBILITY AND INTERLOCKING OF FERTILITY PHASES

The proper coordination of the various fertility phases described above may, for want of a better term, be referred to as a *system*. The objective is, of course, the maintenance of soil fertility at a satisfactory economic level. Since the various phases may or may not all be applied in any given case, the *flexibility* of the system is apparent.

Another feature of the system worthy of particular attention is the influence of its various phases on the effectiveness of the others, that is—*interlocking* effects. For instance, the amount and activity of the organic nitrogen determines the quantity of humus that can be maintained in a soil. Conversely, organic matter decay influences the mobility and availability of the nitrogen. Thus, the control of the one constituent cannot be attained without almost equal consideration of the other.

Lime also affects the other phases of the system in a very decided way. Through its influence on the soil microorganisms, it has much to do with the activity of the organic matter and the availability of the nitrogen. In fact, the vigor with which carbon and nitrogen revolve in their respective cycles is determined in large degree by calcium and other bases. Also the addition of lime undoubtedly at times liberates potash directly and by speeding up organic decay a decided indirect influence is exerted.

The importance of lime in respect to pH adjustment and the efficiency of superphosphate is widely recognized (page 435). Conversely, the potassium and phosphorus by their nutritional effects upon microorganisms and higher plants not only render the application of lime to soils more efficient but also beneficially influence the activity of nitrogen and organic matter.

Although less clearly understood, the trace elements are just as definitely interdependent as are the other phases. Thus, the proper interlocking of all of these features means, in general terms, a well-balanced physiological condition within the soil. This ideal, unfortunately, is seldom fully realized in practice.

20:12. A TEST OF THE SYSTEM

Whatever the combination of fertility factors utilized, their effectiveness can only be proved by actual field tests covering a long period. While much data are available in this respect, certain experiments at the Ohio Agricultural Experiment Station are especially interesting because they employ every means of fertility maintenance except the use of complete commercial fertilizers. (See Table 20:2.)

Table 20:2. Crop Yields on a Set of Plots at the Ohio Agricultural Experiment Station, Average of Twenty-six Years. The full treatment consisted of crop residues, legumes, lime, farm manure, and superphosphate. The rotation was corn, wheat, and clover.[5]

Treatment	*Average Crop Yield per Acre*		
	Corn, Bushels	*Wheat, Bushels*	*Clover Hay, Tons*
1. Full treatment	66.2	28.4	2.34
2. Lacking superphosphate	58.9	23.3	1.95
3. Lacking farm manure and superphosphate	36.8	14.2	1.46

Under conditions of good tillage and drainage, corn, wheat, and clover were grown in the order indicated for twenty-six years, enough plots being used to allow a crop of each to be harvested every year. Lime was added, usually just before the corn was planted. In the full treatment the corn received farm manure at the rate of 8 tons to the acre reinforced with 320 pounds of superphosphate.

The essentials of the system applied to the first group of this series of plats were: crop residues, farm manure, lime, legumes as a crop in a suitable rotation, and superphosphate. Trace elements apparently were not lacking and the soil potash in this particular case was apparently adequate. Ultimately, however, potassium and even the trace elements will probably become deficient and a complete fertilizer will be required. In the second

[5] Williams, C. G., *The Maintenance of Soil Fertility*, Bulletin 381, Ohio Agr. Exp. Sta., 325, 1924.

group of plots noted, superphosphate was excluded, while in the third group both superphosphate and farm manure were withheld.

The deductions from the data presented are so obvious as to need little explanation. Lime not only exerted a favorably and cumulative influence on this soil but also greatly encouraged the clover. The legume, of course, tended to increase or at least maintain the yields of the other crops of the rotation. The average crop yields of the plats receiving the full treatment were over 12 per cent greater during the last half of the period than during the first half. It is difficult to escape the conclusion that such a system may maintain the productivity of certain soils for a considerable number of years.

In spite of the apparent soundness of the above deductions, a word of warning is in order. The fact that crop yields are rising does not necessarily mean that the basic capacity of soils to produce also is going up or even is unimpaired. Far from it. In fact, the inherent productiveness of many field soils is definitely on the down grade. That this is the trend in general is shown by Figure 20:5 which pictures the situation in Ohio [6] since 1870. During this period the basic capacity of Ohio field soils to produce has con-

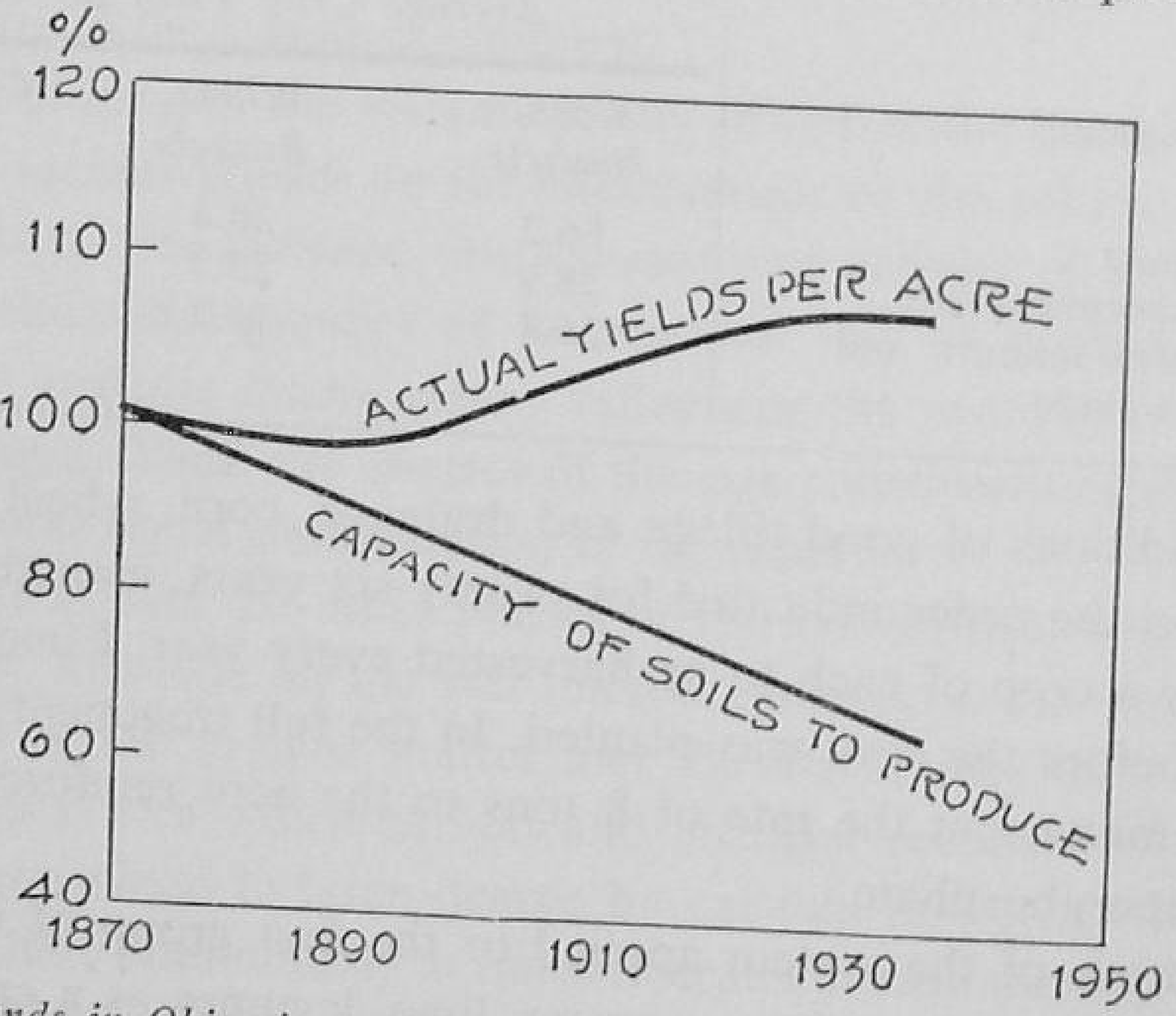


FIG. 20:5. *Trends in Ohio since 1870 as pictured by Salter, R. M., R. D. Lewis, and J. A. Slipher, "Our Heritage the Soil," Extension Bul. 175, Ohio Agr. Exp. Sta. 1941.*

Note that while the inherent capacity of Ohio soils to produce has dropped sharply, actual crop yields have even increased. Apparently new techniques, improved varieties of crops, new lands, tile drainage, and other factors have so far counterbalanced fertility depletion and land exploitations. That they will continue to do so is questionable.

[6] Salter, R. M., R. D. Lewis, and J. A. Slipher, *Our Heritage the Soil,* Extension Bul. 175, Ohio Agr. Exp. Sta., 1941.

sistently waned. Crop yields may ultimately follow when the influence of new techniques, improved crop varieties, drainage, erosion controls and of other factors has passed its peak. Undoubtedly the intensive utilization of every phase of the fertility system may be necessary.

20:13. CROP ROTATION—AN IMPORTANT FERTILITY FACTOR

While the importance of crop residues, farm manure, green manure, legumes, lime, commercial fertilizers, and tillage is fully recognized, few persons realize the benefits that are derived from a suitable crop rotation.[7] The oversight apparently occurs because the average farmer usually has no means of gauging the benefits of alternating his crops, while the influence of farm manure or of commercial fertilizer is generally clearly apparent.

A study of the long-continued field experiments in the United States and in England has brought out some exceedingly important facts regarding the benefits of a good rotation.[8] The more important may be stated as follows:

1. Rotation of crops when practiced with and without fertilizers averaged 75 per cent as effective as the fertilizers in increasing crop yields and 90 per cent as effective when the comparisons were limited to corn, oats, and wheat. In maintaining the productive power of soils in respect to these three crops, the rotation was in general at least 90 per cent as effective as the fertilizers.
2. The benefits of crop rotations did not impair those received from manure and commercial fertilizers. In other words, the effects from the rotations were more or less distinct and did not in any sense take the place of or render unnecessary the use of farm manure or fertilizers.
3. Excluding such crops as clover, timothy, and cowpeas, the average effectiveness of rotations was practically 20 per cent higher on soils that had been limed than those left acid.
4. On soils long under cultivation, the best results were possible only when a crop rotation containing a legume, and receiving farm manure and commercial fertilizers, was used.

For more specific figures respecting the benefits derived from a suitable rotation of crops, reference may again be made to data of the Ohio Agricultural Experiment Station. In this experiment corn, oats, and wheat were

7 Several very good articles dealing with the practical phases of crop rotation will be found in the *Jour. Amer. Soc. Agron.*, Vol. 19, No. 6, 1927.
See also Weir, W. W., *Soil Science*, J. B. Lippincott Company, Philadelphia, 1936, Chap. 24.

8 Weir, W. W., *A Study of the Value of Crop Rotation in Relation to Soil Productivity*, Bulletin 1377, U. S. Dept. of Agriculture, 1926.

grown separately and continuously on the same land for thirty years, receiving each year farm manure at the rate of 5 tons to the acre. At the same time these crops were grown in a five-year rotation of corn, oats, wheat, and two years of clover and timothy. The rotation received 16 tons of manure every five years divided between the corn and wheat. Since this would average only 3⅕ tons of manure yearly, it is obvious that the rotated crops were not favored as to artificial fertilization in comparison with those grown continuously. The yield data are set forth in Table 20:3.

Table 20:3. The Comparative Influence of Continuous Culture and Rotation Cropping upon Yield—Ohio Agricultural Experiment Station, Average of Thirty Years [9]

Treatment	*Crop Yields in Bushels per Acre*		
	Corn	*Oats*	*Wheat*
Continuous culture	33.8	37.8	19.4
Rotation cropping	51.3	43.7	23.5

The results are so striking that little comment is necessary except to suggest that crops grown in sequence probably utilize the soil nutrients more economically than those in continuous culture, and that the rotated crops without a doubt were greatly benefited by the clover. This legume not only acquires nitrogen from the air, if suitably nodulated, but its residues activate the soil constituents as well.

20:14. FERTILITY GENERALIZATION (Before reading this section examine Figure 20:6 and carefully read its legend.)

The system so briefly outlined in the preceding pages is merely a group of practices that are designed, when properly correlated, to maintain, or partially maintain, the fertility and productivity of mineral soils. In some cases all of the features are put into operation, in other cases only a few are employed.

In general and dairy farming the utilization of crop residues, farm manure, legumes, and superphosphate is one of the simplest combinations that can be made of the various fertility factors. Lime may or may not be necessary, while on occasion green manures will be helpful. Because of the rapidity with which potassium deficiencies are now appearing, especially in

[9] Williams, C. G., *The Maintenance of Soil Fertility*, Bulletin 381, Ohio Agr. Exp. Sta., 296–311, 1924.

humid region soils, complete commercial fertilizers are being used more and more frequently. Moreover, trace element deficiencies will need increased attention as time goes on. And whatever may be the fertility combination, its efficiency will be enhanced by a suitable rotation of crops.

FIG. 20:6. *This lush landscape bespeaks a fertile and productive soil. That the owners hope to keep it so is indicated by the strip cropping and the presence of legumes in a rotation that provides abundant organic residues.*

If the other fertility factors are as well taken care of, crop yields will not decline. They may even increase. That trace element deficiencies may sometime appear is probable but an alert county agricultural agent, or even the farmer himself, may anticipate this before crop production is seriously affected. (U. S. Soil Conservation Service photo.)

With intensive vegetable production the main reliance is usually placed upon complete fertilizers in liberal amounts. With certain other crops an adequate supply of nitrogen and the maintenance of the soil organic matter at present may be the only serious considerations. This is the case with apple production on the medium and heavier types of soil. Again, for still other crops such as tobacco and potatoes, potash and phosphoric acid as well as nitrogen are of particular concern.

Satisfactory soil productivity is the ultimate objective of soil utilization. The scheme used is a coordination of certain practices and manipulations

that are designed to best attain this objective. Sound soil fertility management is, therefore, a practical application of edaphological principles and consequently calls for a thorough knowledge of the nature and properties of soils and their relationship to higher plants.

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